

THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XXV

MARCH 1907

NUMBER 2

SECOND PAPER ON THE CAUSE OF THE CHARACTERISTIC PHENOMENA OF SUN-SPOT SPECTRA¹

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In a previous study² of more than two hundred lines photographed in the spectra of sun-spots it was shown that the lines which are strengthened in spots are, in general, strengthened in the laboratory when the vapor producing them is reduced in temperature. The same condition decreases the relative intensity of lines that are weakened in spots. In a note added to the paper it was stated that at least one of the flutings of titanium appears in our photographs of spot spectra. In the present paper we bring forward additional evidence favoring the view that most of the characteristic phenomena of sun-spot spectra are due to a reduction in temperature of the spot vapors below that of the reversing layer.

In an important paper³ Fowler, though apparently inclined to retain his former view of a general intensification of the lines of certain elements in spots, gives some results with which ours are in good agreement. He points out that certain lines of iron, titanium, vanadium, and scandium, which are strong in arc or flame, are

¹ *Contributions from the Solar Observatory*, No. 15.

² George E. Hale, Walter S. Adams, and Henry G. Gale, "Preliminary Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Solar Observatory*, No. 11, *Astrophysical Journal*, 24, 185-213, 1906.

³ *Trans. International Union for Co-operation in Solar Research*, 1, p. 201.

strengthened in spots. He also shows that many enhanced lines are weakened in spots. Fowler's general conclusion is as follows:

The general result of the preliminary discussion is to suggest that, while the enhanced lines of some elements are usually reduced in intensity in the spot spectrum, the arc lines are intensified in accordance with their intensities in the arc-flame, thus suggesting that the additional absorption is produced by relatively cool vapors. This result was, in fact, long ago arrived at by Sir Norman Lockyer, who stated that "many of the lines seen in spots are lines seen at low temperatures (some of them in the oxyhydrogen flame), and none of them are those brightened or intensified when we pass from the temperature of the electric arc to that of the electric spark." Such a reduction of temperature also accords well with the presence of spot bands, as already remarked by Cortie and others.

Fowler's views are thus in perfect harmony with our own, except as regards the cause of the weakening of the "enhanced" lines. On this point he writes as follows:

It is probable that the vapors producing the enhanced lines are chiefly restricted to the higher chromospheric levels, but it is not yet clear whether the reduced intensities in spots is due to the withdrawal of these vapors from over the spot, or to the absence of a sufficiently luminous background to strongly exhibit their absorption (p. 220).

It has seemed to us that, if the strengthening of the flame lines may be accounted for by the reduced temperature of the umbral vapors, the weakening of the spark lines may equally well be attributed to the same cause. This subject, however, is still under investigation.

It is evident, from Fowler's failure to identify the titanium flutings in spot spectra, that photography may be considered to offer special advantages for the study of the fainter lines and bands.

In view of Lockyer's early observations, it is odd that he did not adopt the hypothesis that spots are regions of reduced temperature. He has long held, on the contrary, that at times of sun-spot maximum (when our spectra were photographed) the spot temperature is so high as to dissociate many of the elements represented in the solar spectrum. If, as a paper published before the appearance of our Mount Wilson results indicates, he now believes that sun-spots and red-type stars are cooler than the reversing layer, he may have abandoned or modified his views regarding dissociation in spots.

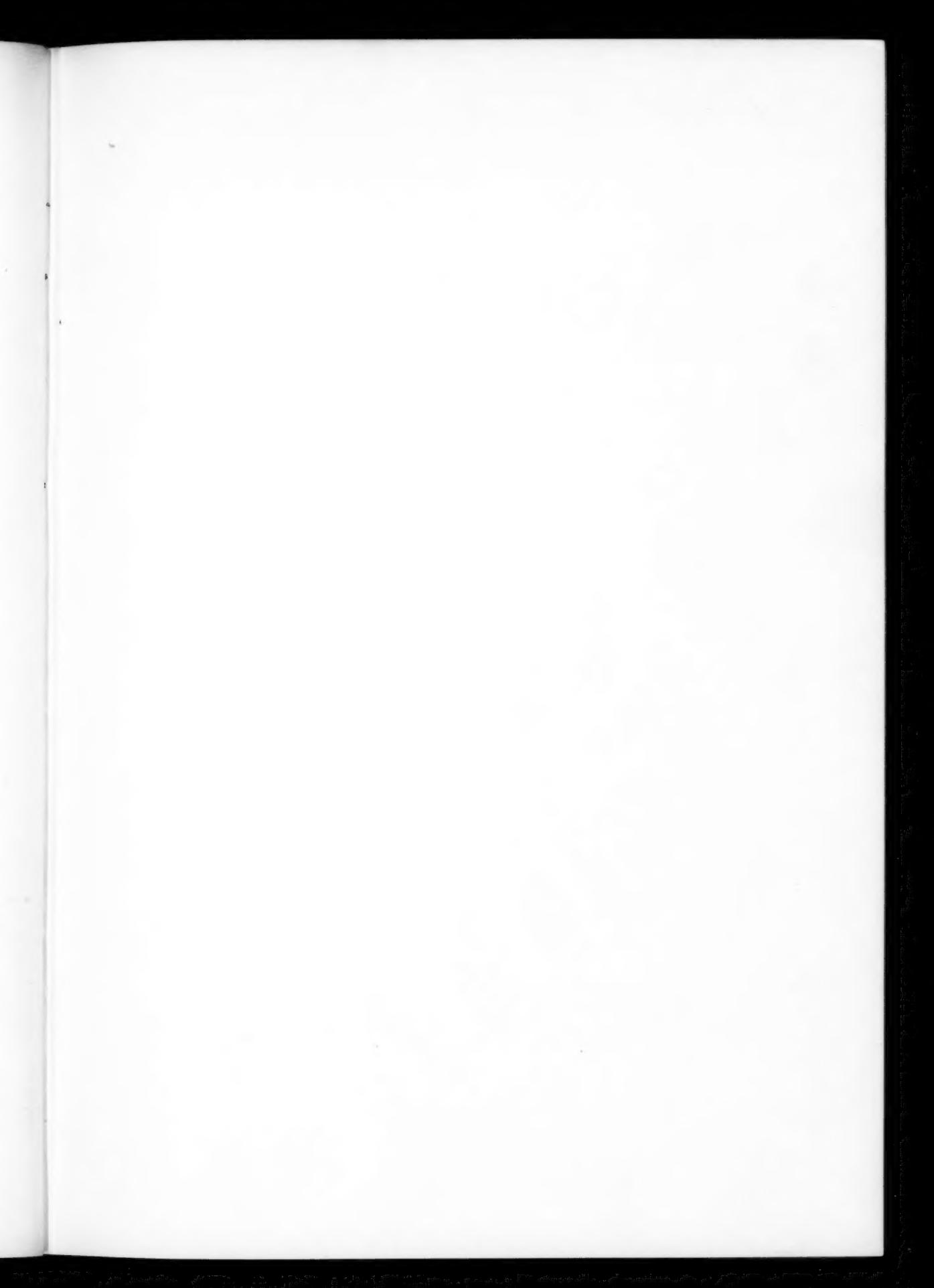
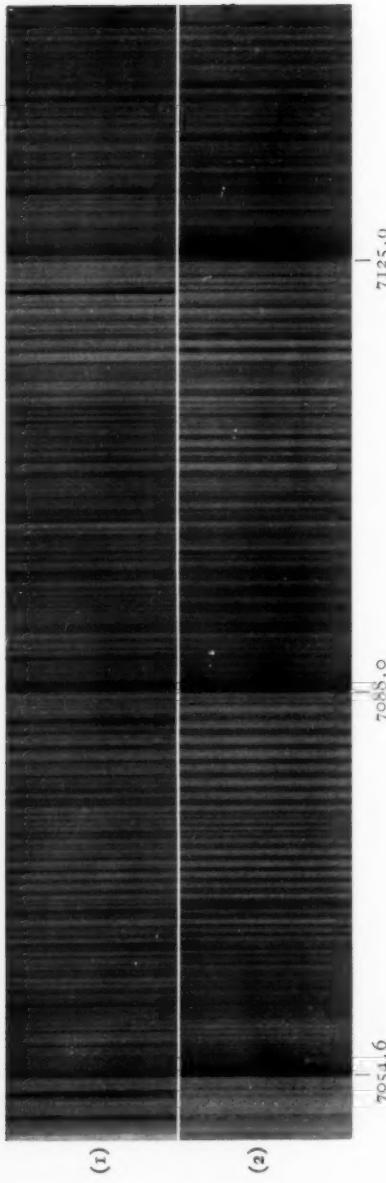


PLATE III



TITANIUM FLUTINGS IN SPECTRA OF (1) SUN-SPOT AND (2) ARC-FLAME.

TITANIUM FLUTINGS IN SPOT SPECTRA

In our study of the spot spectra the titanium fluting of shortest wave-length which we have as yet been able to identify with certainty is that beginning at $\lambda 5598.0$. There seems to be some evidence for the presence of two more refrangible flutings at $\lambda 5166$ and $\lambda 5449$, but it is by no means conclusive. It would, in fact, be somewhat remarkable if these were present upon our plates, since they are much fainter in the titanium flame spectrum than the fluting at $\lambda 5598$, which is very faint and difficult in spots.¹

As we go toward longer wave-lengths, the successive flutings become stronger in the spot spectrum, until in the deep red they form its most characteristic feature. The fluting at $\lambda 7055$ is especially noticeable, as it occurs in a region of the spectrum in which there are but few strong lines to interrupt its continuity. A comparison of this fluting in the spot and in the flame of the electric arc (negative copy) is given in Plate III.

The following tables contain the results of measures of the lines in the spot and the flame spectra, and a comparison of the two with each other and with the corresponding lines in the spectrum of the disk, where such exist. It has seemed desirable to give the evidence in full, not only on account of the importance of the question of the existence of the titanium flutings in spots, but also because of the almost equally important one of their existence in the spectrum of the disk. The results given here, however, are not to be regarded as complete, nor do the coincidences shown represent by any means the total contribution of the titanium flutings to the spot spectrum in this region. The flame spectrum of titanium in the red consists of a large number of flutings and bands, which overlie one another in an extremely complex fashion and contain a vast number of lines. The spectrum of the spot is similar, and a complete comparison of the two will involve a very large amount of measurement, and belongs rather to an exhaustive investigation of the spot spectrum than to the objects of this communication. Enough is given here, we believe, to indicate the nature of the results which a complete study would furnish.

¹ The head of this fluting has been measured upon numerous plates. Only two plates, however, and these taken under exceptionally good conditions, show the fine lines satisfactorily.

The method of procedure which we have followed has been to select the more important of the titanium flutings in the spectrum of the flame of the electric arc and to measure all lines within a considerable distance of their heads. The results are then compared with the lines measured in our photographs of spots. In order to show what proportion of the spot lines is due to titanium, a complete list is given for the regions investigated, except, of course, that the lines identified by Rowland are not included. The arrangement of the tables is as follows: The first two columns contain the wave-lengths and intensities of the lines measured in spots, the third and fourth columns the wave-lengths and intensities of lines given in Rowland's tables which may be coincident with the spot lines, and the fifth column the wave-lengths of the lines measured in the flame spectrum of titanium. We have assumed for the greater part of the spectrum the value of 0.05 tenth-meters as the largest discordance which may exist between lines coincident in spot, disk, and flame, our measures of the stronger lines identified by Rowland indicating ranges of about this amount. In the extreme red this value becomes slightly larger, the character of the lines preventing such accuracy of measurement as can be attained in the more refrangible regions.

An analysis of these tables gives the following results:

Total number of spot lines	234
Coincident with <i>Ti</i> lines	152

Thus about 65 per cent. of the total number of spot lines have corresponding lines in the band spectrum of titanium.

Number of spot lines with <i>Ti</i> coincidences which have possible coincidences in the disk spectrum	42
Identified by Rowland or not coincident with <i>Ti</i> lines	19
Strong lines of <i>Ti</i> or other elements	6
	25
Number of lines in disk coincident with <i>Ti</i> lines	17
Number of spot lines with no <i>Ti</i> coincidences	82
Number of coincidences in disk for these	36

This summary leads to the important conclusion that 43 per cent. of the spot lines with no coincidences in the *Ti* band spectrum, and but 11 per cent. of those with such coincidences, have corresponding lines in the disk. Since the latter quantity is no larger than could

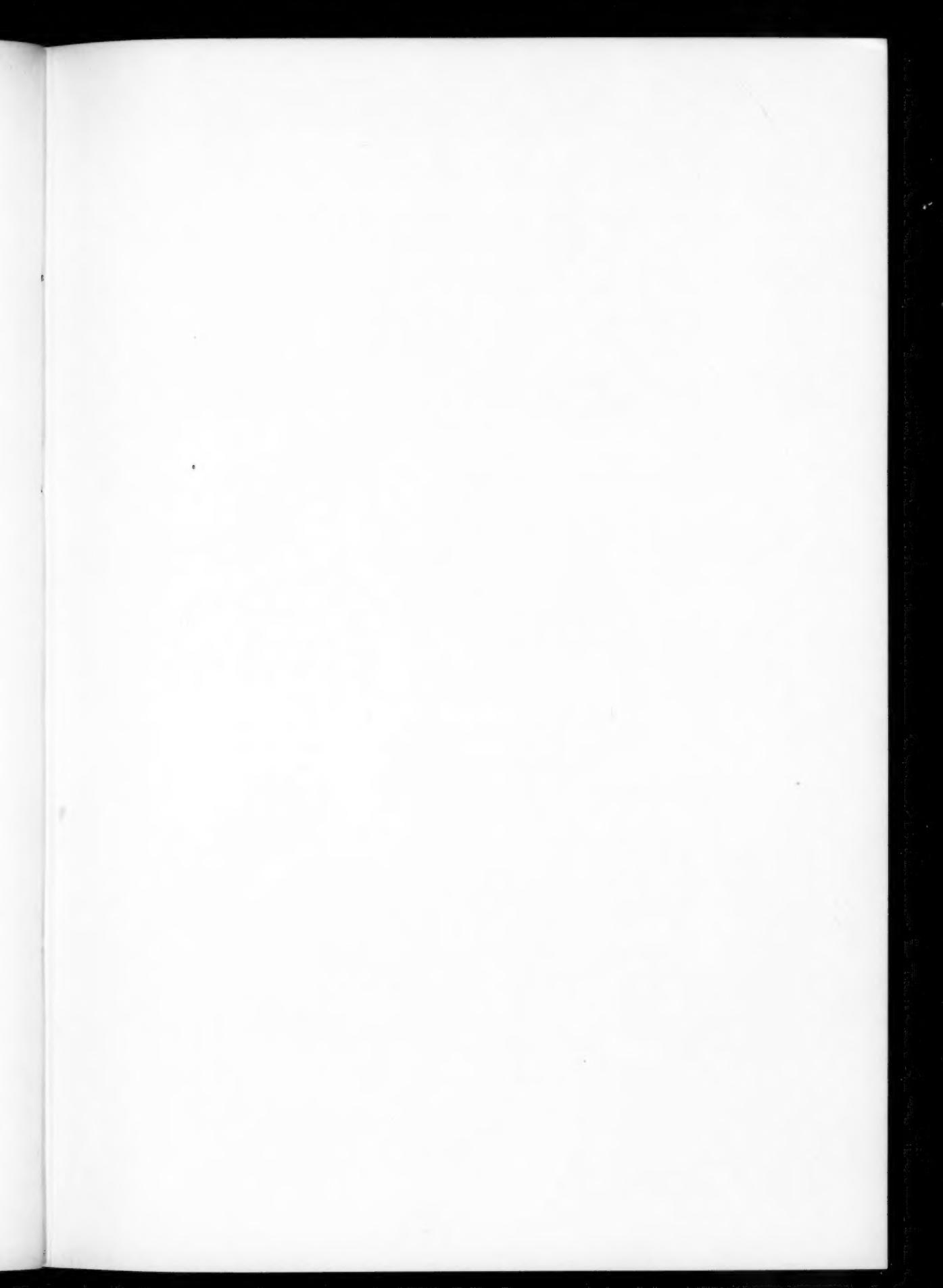


PLATE IV

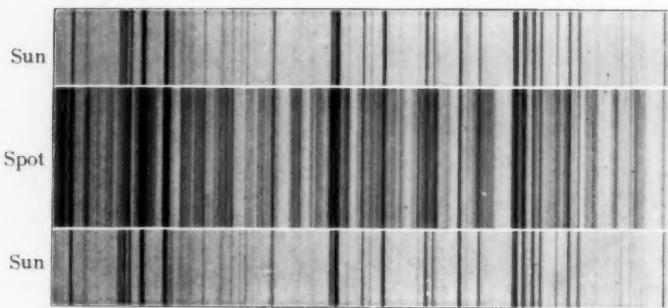


FIG. 1
Region $\lambda 5040-\lambda 5090$

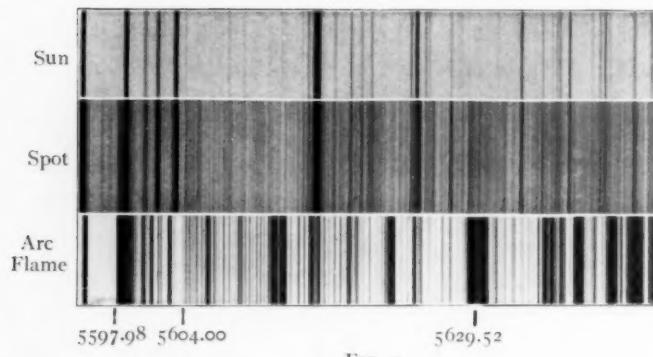


FIG. 2
Titanium Flutings in Spot and Arc Flame.

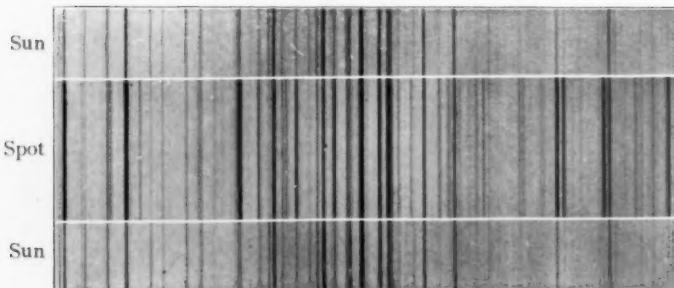


FIG. 3
Region $\lambda 5680-\lambda 5740$

PHOTOGRAPHS OF SUN-SPOT SPECTRA.

TABLE I
COMPARISON OF TITANIUM FLUTINGS WITH SPOT AND SOLAR SPECTRA

SPOT		SUN		Ti	NOTES
λ	Int.	λ	Int.	λ	
5597.98	I	...	....	.99	1st head
5600.79	ooo	...	....	.80	
5608.48	ooo	.52	ooo	.49	
5608.74	ooo	...	....	.74	
5609.04	ooo	...	....	.02	
5609.31	ooo	...	....	.33	
5611.02	oo	...	....	.02	
* * * *	* *	* *	* * *	* *	
5629.52	o-I	...	....	.52	2d head
* * * *	* *	* *	* * *	* *	
6158.84	o-I	.89	ooo	.84	1st head
6159.38	o	...	....	.36	
6164.86	oo	...	....	.90	
6168.00	oo-o	...	....	.00	
6171.41	o	.44	oooo	.40	
6172.18	I	.16	ooo	.16	
6174.41	I	...	....	.45	
6184.72	o	...	....	.67	
6187.82	o	...	....	.82	
6189.02	I-2	...	....	88.97	
6189.58	I	.59	oooo N	...	V 6189.58
6190.12	I	...	....	.11	
6192.42	o	...	....	.39	
6193.02	o-I	...	....	.01	
6193.56	o-I	...	....	.56	
6194.35	o	...	....	.30	
6195.31	oo	...	....	.33	
6195.60	o-I	.66	o N	...	
6197.29	o	...	....	.32	
6197.88	o-i	...	....	.91	
6198.68	I-2	...	....	.64	
6199.84	I	{ .72 .98	oo oooo	{ .84	
6201.20	o-i	.18	ooo	.18	
6201.94	o	...	....	.94	
6202.58	I	...	....	.59	
6202.96	o	...	....	...
6203.38	I	...	....	.38	
6206.60	I	...	....	.59	
6208.08	o-I	...	....	.08	
6208.65	o-I	...	....
6209.17	I	...	....
6209.55	o	...	....
6210.18	2	...	....	.17	
6210.89	5	.90	ooo N	...	Ti line at 6211.02, which is prob-
6211.88	o	...	....	.91	[ably included in this
6212.15	o	...	....	...
6212.48	o	.48	oooo	.45	
6214.07	2	.08	V ooo	.03	
6214.43	o	...	....	...	C _r line at 6214.41
* * * *	* *	* *	* * *	* *	
6262.01	o	...	....	61.99	

TABLE I—Continued

SPOT		SUN		Ti	NOTES
λ	Int.	λ	Int.	λ	
6262.52	o	...	.....	.50	
6262.90	o	...	.....	63.20	<i>Ti</i> line double
6263.45	o	...	.....
6263.99	i	...	.....	.97	
6264.82	i	...	.....	.84	
6266.14	2	{ .55	.....	.16	<i>V</i> 6266.54
66.51			ooo	...	
6269.00	2	{ 68.82	oooo		
		{ 69.08	V ooo N	...	
6274.86	4	.87	oo		<i>V</i> 6274.89
6276.40	o	.45	oooo N	...	
6284.36	o	...	.....	...
6285.34	4	.38	V oo N	...	
6286.17	i	...	.....	...
6286.98	o-i	87.01	oooo N	...	<i>V</i> 6287.02:Cr 6286.95
6289.23	oo	...	.....	...
6289.70	2	{ .61	A (O) i		
		{ .79	oooo	...	Spot line broad
6292.11	o	...	.....	.13	<i>V</i> line at 6292.09
6293.09	6	{ .03	V ooo	{ .09	
		{ .17	A (O) 3		
6296.78	4-5	...	.....	.82	
6297.25	o	...	.....	...
6300.58	o	.54	ooo	.62	
6300.93	o-i	.90	ooo	...	
6303.97	4	.98	ooo N	.98	Strong line of <i>Ti</i>
6305.03	oo	.07	oooo N	...	
6305.90	10	.88	oooo	{ .77	Spot line very broad. Due in part to strong <i>Ti</i> line 6305.77 Cr 6307.19
6307.21	o	...	.....
6307.59	o	...	.....	.55	
6307.99	o	...	.....	08.01	
6308.52	i	...	.....	.47	
6309.72	o-i	...	.....	...	<i>V</i> 6309.74
6311.06	i	.06	oooo	...	
6312.46	3	.46	oo N	.46	Strong line of <i>Ti</i>
6313.18	i-2	...	.....	.14	
6313.72	o-i	...	.....	...
6314.47	i	.45	A (O) o	.42	
6316.62	i	{ .51	A(wv)ooooN	.54	Spot line very broad
		{ .82	oooo	...	
6322.02	o-i	...	.....	...
6323.53	i	...	.....	.51	
6324.70	o	.71	A (O) oo	.74	<i>V</i> line at 6324.74
6325.39	2	.38	oooo	.34	
6326.34	o-i	...	.....	...
6327.11	i	...	.....	.13	
6331.80	i	...	.....	...
* * *	* *	* *	* * *	* *	
6651.62	2	...	.....	.56	1st head
6652.32	oo-o	...	.....	.30	
6653.19	oo	.22	oooo	.24	
6653.80	54.89	i	.....	54.44	Broad patch in both spot and <i>Ti</i>

TABLE I—Continued

SPOT		SUN		Ti	NOTES
λ	Int.	λ	Int.	λ	
6655.21	oo	...	.....	...
6656.67	o-I	.62	oooo	.67	
6657.25	o-I	.20	ooo N	.27	
6657.99	o-I	...	.....	.96	
6658.58	o	...	.....	.54	
6659.20	o	.16	oooo	...	
6660.78	o-I	.83	oooo	...	
6661.37	I	.32	Cr oo	.32	
6662.08	oo	{ 62.01	oooo N	61.99	Broad in spot
6662.67	o	...	.....	...
6664.83	I	...	.....	.79	
6665.55	I	...	.....	.52	
6666.63	o .77	{	.....	.70	2d head Practically a band in spot
6667.24					
6668.03	o	...	.....	.02	
6668.03	oo	.64	ooo N	...	
6669.06	o	.04	oooo N	.01	
* * * *	* *	* *	* * *	* *	
6681.11	I	...	.....	.11	
6681.65	oo	...	.....	.62	
6682.34	oo	...	.....	.30	
6682.91	oo	...	.....	...
6683.63	oo	...	.....	.65	
6684.96	oo	...	.....	...
6686.10	o-I	...	.....	.11	
6687.78	I	.75	oooo	...	
6688.28	oo	...	.....	...
6689.06	o	...	.....	...
6689.59	oo	...	.....	...
6690.14	I-2 91.44	{	....	...	A broad band in spot
6691.91					
6692.83	oo	...	.....	.95	
6693.62	o	...	.....	.80	
6694.58	oo-o	...	.....	.61	
6695.53	oo	...	.....	.56	
6697.19	oo	...	.....	.51	
6698.12	oo	...	.....	...
6698.87	2	.91	o	.10	
6699.90	o	...	.....	.84	
6700.36	oo	...	.....	.92	
6700.82	oo	...	.....	{ .64	Ti line double
6701.67	o-I	.62	ooo	.65	
6704.82	oo	...	.....	.86	
6705.85	o	{ .75	oooo	{ .86	
6706.80	o	.94	oooo	...	
6707.39	oo	...	...	...
6708.13	4	.18	oooo	...	
6709.23	o	.23	oooo N	.24	
6710.57	I	.57	o	...	
6711.49	o	.53	oooo	.52	

Ca 6708.15

TABLE I—Continued

SPOT		SUN		<i>Ti</i>	NOTES
λ	Int.	λ	Int.	λ	
6711.98	oo	...	.....	...
6712.57	oo	...	.....	...
6713.09	o	...	.....	.14	
6714.30	I	...	.....	.25	
6714.80	oo	...	.....	.82	
6715.59	2	.64	I	.54	
6716.12	oo	...	.....	.17	
6716.98	o	...	.....	.95	
6718.49	oo	...	.....	...
6719.84	I-2	.88	ooo N	.86	Strong line of <i>Ti</i>
6720.49	oo	...	.....	...
6721.18	oo	...	.....	.18	
6721.66	oo	...	.....	.65	
6722.24	2	...	.....	.24	
6722.75	oo	...	.....	.78	
6723.74	oo—o	...	.....	.76	
6724.20	oo—o	...	.....	.19	
6724.60	oo	...	.....	...
6725.27	o	.22	oooo	...	
6725.89	o	...	.....	.86	
6726.30	oo—o	...	.....	.26	
6727.30	oo	...	.....	...
6728.53	I	...	.....	.48	
6729.26	I	.27	oo	.22	
6730.05	oo	.00	ooo N	...	
6730.56	oo	.56	ooo N	.55	Fairly strong <i>Ti</i> line
6731.08	o	...	.....	.56	Broad patch in spot
31.83	}				
6731.96	..	...	.....	.94	Bright streak in spot: dark space
6732.83	I-2	..	.....	.06	[in <i>Ti</i>] Broad band
34.00					
6735.31	oo	.28	oooo	...	
6735.79	o	...	.....	.77	
6736.36	o	...	.....	.23	
6737.28	o	...	.....	.30	
6738.07	o	...	.....	.07	
6738.70	2	...	.....	.65	
39.79	}	.78	o	...	Broad band in spot
6740.57	oo	...	.....	...
6740.82	o	...	.....	.83	
6741.72	2	...	.....	42.12	
42.44					
* * * *	* *	* *	* * *	* *	
7054.60	2	...	.....	.65	Strong head in both spot and <i>Ti</i>
* * * *	* *	* *	* * * *	* *	
7060.32	o	.35	oooo N	...	
7060.73	oo	...	.....	...
7070.40	I-2	...	.....	.37	
7071.35	I	...	.....	.30	
7072.29	I-2	...	.....	.27	Spot line includes solar 7072.13
7072.75	oo	.72	ooo	...	
7073.27	I	...	.....	.29	

TABLE I—Continued

SPOT		SUN		Ti	NOTES
λ	Int.	λ	Int.	λ	
7074.18	oo—o	...	.....
7074.54	oo	...	.....	.33	
7075.15	o	.19	oooo		
7076.18	o	...	.....
7076.72	oo—o	...	.....
7077.23	oo	...	.....	.15	
7077.99	I—2	...	.....
7078.29	o	...	.....	78.10	
7079.24	2	...	.....	.26	
7080.47	I	...	.....	.47	
7081.68	I	...	.....	.69	
7082.96	I—2	...	.....	.96	
7084.25	I—2	.24	ooo N	.24	Fairly strong line of Ti
7086.66	oo	.59	oooo		
7087.90	I—2	...	.....	88.00	2d head of fluting
7089.28	oo	...	.....
7091.41	oo	.43	oooo		
7092.20	oo	.22	ooo N		
7092.85 {	2	...	.....	93.3 {	Broad band in spot; very broad, hazy, and poor in Ti
93.65 }					
7094.79	oo	...	.....	95.00	
7095.16	oo	...	.....
7096.12	o	.14	ooo		
7096.63	o	.66	oooo		
7097.50	o	...	.....
7099.19	o	.22	oooo N		
7099.83	I	.81	oooo N	.77	
7101.31	I	...	.....	.35	
7102.63	I—2	.56	ooo N		
7103.26	o	...	.....
7104.63	o	...	.....	.65	
7105.02	oo	...	.....
7106.36	I	.43	A ?oooNd?	.59	
7106.77	I	...	.....
7108.13	oo	.19	oooo N		
7108.75	o	...	.....
7109.91	o	...	.....	.87	
7110.66	oo	.70	oooo N		
7111.75	I	.73	A ooo N	.73	
7112.87	oo	...	.....
7113.91	oo	.87	oooo		
7116.29	o	...	.....
7117.34	I—2	...	.....	.37	
7118.52	I—2	.55	A I		
7119.21	oo	.25	oooo		
7119.93	oo	.96	ooo N		
7120.16	oo	...	.....	20.00	
7120.43	oo	...	.....
7121.21	o	...	.....	.25	
* * * *	* *	* *	* * *	* *	
7125.89	2	...	.....	.88	3d head of fluting

be accounted for by accidental coincidences within the limits of accuracy of the measures, the conclusion is justified that the titanium flutings are not present in the spectrum of the disk. This conclusion is greatly strengthened by the fact that of the nine heads of flutings which have been measured in spots and in the flame, and which are conspicuous as compared with the remainder of the lines of the band spectrum, only one has a possible counterpart in the spectrum of the disk. It seems certain, therefore, that the temperature of the reversing layer is normally too high to admit of the presence of the band spectrum of titanium.

SPARK¹ LINES IN THE RED

Though our comparison of spot lines with the spectra of the various elements is as yet very incomplete, and we have no plates extending to wave-lengths greater than $\lambda 6700$ for any except titanium, some results already found for the lines enhanced in the spark, and for a few lines strengthened in the flame spectrum, are of sufficient interest to warrant their inclusion here.

The following list includes the more important of the spark lines of iron, titanium, and nickel, and indicates their behavior in spots.² The amount of enhancement in the spark is given on a scale of 0 to 5.

¹ Since the beginning of this investigation, we have been troubled by a question of nomenclature. Lockyer has applied the appropriate name "enhanced line" to a line that is strengthened in the spark, as compared with the arc, and this designation is now generally used in the literature of spectroscopy. No suitable name has been suggested for lines that are strengthened in the flame or the arc, where the "enhanced lines" are weakened. In any event, confusion is likely to result from the fact that the lines which have always been regarded as characteristic of sun-spots—those which are more conspicuous in the spot than in the solar spectrum—are not "enhanced" lines. On the contrary, they are lines that are strengthened in the flame; the "enhanced" lines are weakened in spots. In the present paper we have thought best to adopt the old terms "spark line" and "flame line" for lines strengthened in the spark or flame, respectively. It is, of course, well understood that spark lines do not exist exclusively in the spark, or flame lines in the flame. The intensity of spark lines increases as the temperature rises, while that of the flame lines increases as the temperature falls.

² As the question of impurities has not yet been fully investigated, some of these lines may arise from foreign sources, though they would still seem to belong in the list of spark lines.

IRON

	Enhancem't in Spark	Intensity in Sun	Intensity in Spot	
6042.32	1	Fe 3	2	
6103.40 } .51 }	1-2	Fe 4 } — 1 }	4	
6147.95 } .48.04 }	3	— 2 } Fe 3 }	3	
6149.46	3	— 2	0	
6238.60	3	— 2	0	
6247.77	5	— 2	00	
6315.52	1-2	Fe 2	1	
6380.96	1	Fe 4	1	Rowland's intensity too high. Complicated in spark by air line
6417.13	2	Fe ? 1	00	
6420.17	1	Fe 4	2-3	
6456.60	5	— 3	0-1	
6516.31	1-2	— 2	00	
6560.46	1-2	Fe 5	4	Complicated in spark by air line
6627.80	1-2	Fe ? 0	00	
6663.49 } .70 }	1	— 1 } Fe 3 }	3-4	

TITANIUM

6491.80	2	— 1	00-0	
---------	---	-----	------	--

NICKEL

6110.97	1	Ni 0	00	Difficult in spot on account of V 6119.74
6125.24	2	— 1	00-0	
6130.34	1	Ni 1	0	

The above list affords strong additional evidence for the conclusion that spark lines are weakened in the spectra of spots.

FLAME LINES IN THE RED

In view of the importance of accurate determinations of changes in line intensities in passing from the core of the electric arc to the flame, it has seemed desirable to take up this side of the investigation with a photometer especially adapted for the purpose. Accordingly, we have as yet made no systematic examination of the lines strengthened in the flame for the red region of the spectrum. A few cases, however, are so striking that they are deserving of comment.

The following table indicates the behavior in this regard of two lines of calcium and two lines of sodium. The amount of strengthening in the flame as compared with the core of the arc is on a scale of 0 to 5.

CALCIUM

	Strengthening in Flame	Intensity in Sun	Intensity in Spot
6573.03	5	Ca ? 1 0000	8
6708.18	4		4*

* It is not certain that this line is due to calcium, as it appears strongly on plates of several other elements. It is in every case greatly strengthened in the flame.

SODIUM

6154.44	2	Na 2	5-6
6160.96	3	Na 3	5

The two calcium lines given above show the largest increase of intensity in passing from the core of the arc to the flame of any lines which we have encountered. The remarkable degree to which they are affected in spots also makes them conspicuous among the spot lines.

MOTION OF SPOT VAPORS IN THE LINE OF SIGHT

The importance of the question of the motion in the line of sight of the spot vapors as bearing on any theory of spot structure, is of course, very great, and has been kept in mind in the investigation of our observational material. In the method which we have adopted of photographing spot spectra it is necessary to make the exposures on spot and disk separately, occulting one while the other is being photographed. For this purpose an occulting bar is moved across the slit by means of a rack and pinion, as in most stellar spectrographs. Accordingly, the danger of errors arising from instrumental sources should not be great.

The study of the plates has led to the conclusion that there is as a rule very little motion in spot umbrae. Out of eighty plates of eleven spots only two gave any reasonably certain displacements of the spot lines, and even in these two cases the values were close to the limit of accuracy of the measures. In both instances the motion

was directed downward, and amounted to about 0.2 km a second. In one case, moreover, the motion was certainly temporary, since plates of the same spot taken on the following day gave no displacements whatever. The general conclusion, then, seems to be justified that the vapors forming the umbra of a well-developed spot are normally nearly at rest, with perhaps some presumption of a slow downward drift. This result is in agreement with that found by Mitchell from the study of a large number of spots during 1904-5. He says: "Line-shifts in the spot-spectrum, with the exception of those due to hydrogen, are very rare."¹

EFFECT OF DENSITY

The suggestion has been made that the relative intensities of lines observed in spots and in the laboratory may be due to the increased density of the vapors producing them. To test this question, the following experiments have been made in our spectroscopic laboratory by Dr. Olmsted.

The spectrum of a 30-ampere arc, between iron poles, was compared with that of a 2-ampere arc, between carbon poles containing only a trace of iron. The changes in the relative intensities of the lines were similar to those observed in passing from the ordinary solar spectrum to that of sun-spots. Moreover, a 2-ampere arc between iron poles gave the same spectrum as the 2-ampere arc between carbon poles, with but little iron present.

A spark between iron poles, with no self-induction, was compared with a spark between one iron and one carbon pole, with self-induction to cut down the temperature. The changes of relative intensity were those observed in all other cases when the temperature is reduced. Two carbon poles, with a small amount of iron filings present, and two iron poles, both with self-induction, gave the same relative intensities of the lines.

Similar experiments were tried with manganese and calcium, in both the spark and the arc. In all cases the relative intensities of the lines seemed to depend simply upon the strength of the current, or the amount of self-induction, and to be entirely independent of the density of the radiating vapor.

¹ *Astrophysical Journal*, 22, 38, 1905.

THE TEMPERATURE OF SUN-SPOTS

The presence of the titanium flutings in spots, and their apparent absence from the ordinary solar spectrum, strongly confirm the view that the umbral vapors are cooler than those of the reversing layer. It is not yet certain that these flutings are due to the oxide, but they presumably represent a molecule that is dissociated at high temperatures. The fundamental differences between line and band spectra—for example, the fact that flutings are unaffected by pressure or by a magnetic field—are generally held to indicate that they arise from different aggregations; in short, that lines represent the atom, while bands represent the molecule.

In our laboratory experiments the strengthening of flame lines and the weakening of spark lines have always appeared to be associated with reduction of temperature. Crew's work has shown that rapid change of potential is an effective means of strengthening spark lines, but it almost certainly involves a momentary increase of temperature, and in any case cannot be considered the only possible mode of altering the relative intensities. The theoretical considerations so ably summarized by Crew in his recent address before the American Association¹ seem to favor the view that the relative intensities of spectral lines are more easily influenced by some electrical cause than by change of temperature. But how can the results of our experiments with so many different sources be accounted for in this way? We fail to see, for example, how electrical causes could have operated in our furnace, especially after the arc, which played on the *outer* walls of the carbon tube containing the metal, had been extinguished. It seems almost certain that in this case the relative intensities of the lines were determined by the temperature, or by chemical action, which might be a function of the temperature. The range of temperature obtainable in our furnace was hardly sufficient to produce unquestionable changes in the relative intensities of lines, though there seem to be some cases of this kind in the case of chromium. Pending the continuation of this work, we cannot claim to have done more than to prove that the changes of relative intensity from a 30-ampere to a 2-ampere arc, and from core of arc to flame, resemble

¹ *Science*, January 4, 1907.

those from core of arc to furnace. However, the flame is undoubtedly cooler than the core of the arc, and in the furnace the temperature was too low to melt titanium. Moreover, the well-known changes in the relative intensities of the calcium lines, in passing from the Bunsen burner to the oxyhydrogen flame, certainly indicate that temperature is quite as competent as change of potential to produce these phenomena.

The simplest way to account for the relative intensities of lines in the spectra of sun-spots and third-type stars is to assume that reduced temperature in these sources is the effective cause. For, on the one hand, the presence of the titanium flutings, which consistently rise and fall in intensity with the flame lines in all of our sources, and are absent from the solar spectrum, leaves little doubt that the vapors in sun-spots and third-type stars are cooler than the corresponding vapors in the reversing layer. On the other hand, laboratory experiments have shown that changes of temperature may produce, either directly or indirectly, just such spectral phenomena as those here involved. It therefore seems entirely unnecessary to assume that electrical phenomena, or other such causes, are at work, though their operation is not necessarily excluded.

Although we are thus inclined to regard the relative intensities of spot lines as resulting from reduced temperature, we by no means consider this cause competent to explain the many peculiarities exhibited by spot spectra. The existence of winged lines, for example, may depend upon the density and perhaps upon the level of the corresponding vapors. Further reference to this question is made below. A more complete investigation, however, will demand much work in the future.

STRATIFICATION OF THE VAPORS IN SUN-SPOTS

We now pass to the difficult task of examining a few of the complex details of spot spectra, for the purpose of interpreting them in accordance with some rational view of sun-spot structure. We are called upon to account for the following phenomena, among others perhaps equally important:

1. The gradual decrease, as we proceed toward shorter wavelengths, in the amount by which spot lines are affected, and the close

agreement in the ultra-violet of the spot spectrum with the solar spectrum.

2. The presence in spots of the strong and sharply defined lines of the titanium line spectrum, together with the faint flutings of the band spectrum.

3. The fact that all of the sodium lines, about 80 per cent. of the calcium lines, and about 25 per cent. of the chromium, iron, and manganese lines are accompanied by wings, while none (or very few) of the lines of titanium or vanadium are thus affected.¹

4. The reversals of spot lines observed by Young and Mitchell.

Although no complete discussion of these points can be attempted until more laboratory work has been done, their brief consideration at the present time may aid to clear the way for further investigations. The great similarity between the spot and solar spectrum in the ultra-violet may be regarded as the maximum development of a tendency which has already become very marked in the violet region. The gradual decrease in the amount by which titanium and vanadium spot lines are affected, as we pass from the yellow through the blue to the violet, and the decrease in the number of strengthened lines of iron in the blue and violet, are strong indications of such a tendency. The changes in the relative intensities of the lines observed in the laboratory show no such marked falling-off in the more refrangible region. For this reason it seems probable that many of the spot phenomena depend upon the level of the umbral vapors in the solar atmosphere.

In our previous paper we made the purely tentative hypothesis that the gradual weakening of the spot spectrum and its replacement by an almost unmodified solar spectrum in the ultra-violet might be attributed to the presence of the ordinary reversing layer over the umbral vapors. The absorption and scattering of the more refrangible spot radiations within this layer, and especially within the spot itself, would greatly decrease their intensity, while the superposed reversing layer would produce the ordinary solar spectrum. However, the difficulty of accounting for a condition of affairs in which the

¹ These figures were derived from a study of over 400 of the strengthened lines in the region from λ 4800– λ 7300. If wings could be seen on the fainter lines, these percentages would doubtless be modified.

reversing layer, undiminished in temperature (as indicated by the unchanged relative intensities of its lines), actually overlies the umbra and penumbra, is very great. It would seem that the temperature of vapors overlying a sun-spot must be lower than that of the corresponding vapors in the reversing layer above the photosphere, both because of the absence of strong convection currents, and because of the diminished radiation from the spot, due to the absorption and scattering of the radiation proceeding from below the umbra and the comparatively low temperature of the spot vapors. Our measures of the sun-spot lines, as explained elsewhere, show very few evidences of motion in the line of sight. In the instances when motion was detected it was directed downward. This result would be in harmony with our knowledge of other spot phenomena. It is a well-known fact, for example, that eruptions rarely or never occur in the umbra, but almost invariably at a point outside of the penumbra or in a "bridge." It would consequently appear improbable that convection currents, such as offer visible evidence of their presence in the photosphere, are to be regarded as existing in the umbra. If the umbral vapors overlie the photosphere, convection currents may possibly rise from the interior below them. Their effect upon the temperature of the region above the umbra, however, would certainly be greatly diminished by the strong absorption and scattering of the spot vapors.

It is thus difficult to see how the unchanged reversing layer can exist over sun-spots. How, then, are we to account for the presence of the ordinary solar spectrum in the ultra-violet region? We have shown in previous papers that the relative brightness of the umbra as compared with the photosphere is much smaller in the violet than in the red. At $\lambda 4000$, for example, the spot spectrum must be exposed about eleven times as long as the spectrum of the disk, in order to get a negative of equal intensity, while in the yellow an exposure six times as long will suffice to give such a result.¹ The long exposure required in the violet for the spot spectrum has suggested the possibility that two principal sources, from which a solar spectrum might be derived, must be taken into account:

1. Sunlight scattered in the earth's atmosphere.

¹ The ratios were incorrectly given in our previous paper.

2. Light from the photosphere, brought upon the slit by atmospheric disturbances during the exposure.

Sunlight scattered by small particles lying above the umbra (such as produce the solar spectrum observed in the inner corona), and diffuse light in the spectroscope, may also be involved, but probably in very small degree.

It is easy to determine the approximate intensity of the scattered light in our atmosphere. Photographs of the spectrum of the sky near the sun, taken for this purpose, showed that under the conditions existing at the time the sky spectrum at $\lambda 4000$ was about one-tenth as bright as the spectrum of the center of the sun's disk. Our observations indicate the presence of certain spot lines, and consequently a very appreciable value for sun-spot radiation, much farther to the violet than $\lambda 4000$. At present we have a considerable number of lines in the ultra-violet reaching as far as $\lambda 3662$, and under the finest conditions of definition of the solar image this limit might perhaps be extended farther. In this region the intrinsic brightness of the sky would be appreciably greater than at $\lambda 4000$, and, in the longer exposure required to photograph the spot spectrum, the sky spectrum would appear on the plate with considerable intensity. In the less refrangible region of the visible spectrum, however, it would be much fainter, and perhaps hardly perceptible, partly because of its smaller intrinsic brightness, and partly because the exposure required for the spot is relatively much shorter than in the violet.

The effect of the photospheric light which enters the slit, because of the unsteadiness of the solar image, must always be appreciable in exposures of any considerable length. The rapid decrease in the exposure time required to photograph the spectrum of the umbra of a spot, when the definition of the sun's image becomes poor, is excellent evidence of the importance of this fact. Among other causes which would tend to introduce photospheric light into the spot spectrum would be astigmatism, due to distortion of the mirrors by heating; change of focal length during the exposure, resulting from the same cause; and unsteadiness of the spot image upon the slit, due to imperfect guiding.

The combined effect of these various causes would undoubtedly

account for the presence of an ordinary solar spectrum in the ultra-violet region of spot spectra. Whether its intensity would be as great as the observed intensity cannot be certainly determined until further quantitative studies have been made.¹

In seeking to account for the phenomena enumerated (2) to (4), page 90, let us tentatively make the hypothesis that the minimum temperature and the maximum density of the spot vapors occur in the lower part of the umbra. We know little or nothing as to the nature of the radiation which proceeds from the photosphere or from any other source that may underlie the umbra. In any case, however, the intensity of this radiation must be greatly diminished by absorption and scattering in its transmission through the spot. The faintness of the wings accompanying so many of the lines, and the greater frequency of the winged lines in the less refrangible region, would seem to indicate that the radiation of the vapors which are dense enough to produce these wide wings must proceed from a very considerable depth, and thus be subject to strong absorption and scattering, which should be most marked in the more refrangible region. Again, we have the case of the titanium spectrum, in which the flutings are faint while the lines are strong and well-defined, in no instances (or very few) being accompanied by wings. The band spectrum, according to the generally accepted view, is due to the molecules, which will be most numerous in the region of lowest temperature. It should consequently be subject to more absorption and scattering than the line spectrum, and therefore be comparatively faint. Moreover, the flutings should rapidly grow fainter in the more refrangible region, which is the case.

The line spectrum, originating for the most part in a region of higher temperature, where the vapor is less dense, should give sharp lines, without wings. Comparing the titanium spectrum, therefore, with the spectrum of sodium, iron, or any other metal of low melting-point, we may say that the spot temperature is low enough to produce a band spectrum only in the case of so refractory a substance as titanium; whereas in the case of the other metals, the line spectrum is produced throughout the entire depth of the spot vapors.

¹ For an interesting discussion of these questions which has reached us since the above was put in type, see Newall, *Monthly Notices*, January 1907.

If this purely tentative hypothesis be sound, vanadium should behave much as titanium does, on account of its high melting-point. Hitherto, however, we have not been able to produce a vanadium band spectrum in the laboratory, or to identify it in spots. We are continuing our investigations on this subject in the hope of making the test.

The hypothesis that the temperature of the spot vapors is higher in their upper part provides the simplest way of accounting for the existence of bright reversals of some of the spot lines, observed by Young and Mitchell. The question whether the lines will be reversed or not depends upon the temperature and density gradients of the vapors, just as in the case of the electric arc. If a sufficient difference of temperature exists, and the upper vapors are dense enough, reversals will occur. It is evident, however, that this subject will require much further study, made with special reference to the individual peculiarities of the reversed lines.

JANUARY, 1907

ARBITRARY DISTRIBUTION OF LIGHT IN DISPERSION BANDS, AND ITS BEARING ON SPECTROSCOPY AND ASTROPHYSICS¹

BY W. H. JULIUS

In experimental spectroscopy, as well as in the application of its results to astrophysical problems, it is customary to draw conclusions, from the appearance and behavior of spectral lines, as to the temperature, density, and motion of gases in or near the source of light. These conclusions must in many cases be entirely wrong, if the origin of the dark lines is exclusively sought in absorption, and that of the bright ones exclusively in selective emission, without taking into account the fact that the distribution of light in the spectrum is also dependent on the anomalous dispersion of the rays in the absorbing medium.

It is not in exceptional cases only that this influence makes itself felt. Of the vapors of many metals it is already known that they bring about anomalous dispersion with those kinds of light that belong to the neighborhood of several of their absorption lines.² In all these cases the appearance of the absorption lines must to a greater or less extent be modified by the above-mentioned influence, since the mass of vapor traversed by the light is never quite homogeneous. Hence it is necessary to investigate the effect of dispersion on spectral lines separately; we must try to distinguish it entirely from the phenomena of pure emission and absorption.

The previously described experiments with a long sodium flame,³ in which a beam of white light alternately traveled along different paths through that flame, constitute a first attempt in this direction. With these relative displacements of beam and flame the rays of the anomalously dispersed light were much more bent, on account of the

¹ The main part of this paper was communicated at the meeting on September 29, 1906, of the Royal Academy of Sciences of Amsterdam.

² After Wood, Lummer and Pringsheim, Ebert, especially Puccianti has investigated the anomalous dispersion of various metallic vapors. In *Nuovo Cimento*, (5) 9, 303, 1905, Puccianti describes over a hundred lines showing the phenomenon.

³ W. H. Julius, "Dispersion Bands in Absorption Spectra," *Proc. Roy. Acad. Amst.*, 7, 134-140, 1904; *Astrophysical Journal*, 21, 271, 1905.

uneven distribution of the sodium vapor, than the other rays of the spectrum; absorption and emission changed relatively little. The result was that the distribution of the light in the neighborhood of D_1 and D_2 could be made very strongly asymmetrical, which could easily be explained in all details as the result of curvature of the rays. The existence of "dispersion bands" was thus proved beyond doubt.

But the pure effect of emission and absorption was not absolutely constant in these experiments, and only conjectures could be made concerning the density of the sodium vapor in the different parts of the flame. Moreover, the whirling ascent of the hot gases caused all rays, also those which suffered no anomalous dispersion, to deviate sensibly from the straight line, so that the phenomena were too complicated and variable to show the effect of dispersion strictly separated from that of emission and absorption. So our object was to obtain a mass of vapor as homogeneous as possible and, besides, an arrangement that would allow us to bring about arbitrarily, in this vapor, local differences of density in such a manner that the average density was not materially altered. The absorbing power might then be regarded as constant. At the same time it would be desirable to investigate the vapor at a relatively low temperature, so that its emission spectrum did not have to be reckoned with.

In a series of fine investigations on the refractive power and the fluorescence of sodium vapor, R. W. Wood¹ caused the vapor to be developed in an electrically heated vacuum tube. It appeared possible, by adjusting the current, to keep the density of the vapor very constant. Availing myself of this experience, I made the following arrangement for the investigation of dispersion bands.

APPARATUS

NN' (see Fig. 1) is a nickel tube of 60 cm length, 5.5 cm diameter, and 0.07 cm thickness. Its middle part, having a length of 30 cm, is placed inside an electrical furnace of Heraeus (pattern E 3). Over its extremities covers are placed, the edges of which fit into circular rims soldered to the tube, which consequently shut air-tight when the rims are filled with cement. When the furnace is in action, a steady current of water, passing through the two mantles M and M' , keeps

¹ *Phil. Mag.*, (6) 3, 128; 6, 362, 1903.

the ends of the tube cool. Each of the two caps has a rectangular plate-glass window, and also, on both sides of this, openings *a* and *b* (*b'* and *a'*), placed diametrically opposite to each other and provided with short brass tubes, the purpose of which will appear presently.

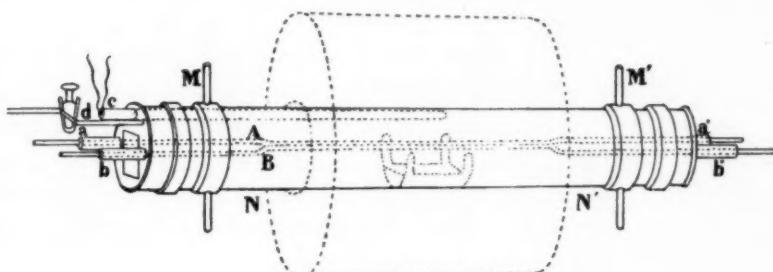


FIG. 1

Moreover, in one of the two caps (see also Fig. 2) two other short tubes *c* and *d* are fastened in openings; through *c* the porcelain tube of a Le Chatelier pyrometer is fitted air-tight, while on *d* a glass cock with mercury lock is cemented, leading to a manometer and a Geryk air-pump. As soon as the sodium (a carefully cleaned piece of about 7 grams) had been pushed to the middle of the tube in a small nickel dish provided with elastic rings, the tube was immediately closed and exhausted.

We shall now describe the arrangement by which arbitrary inequalities in the density distribution were produced inside the mass of vapor. It consists of two nickel tubes *A* and *B* of 0.5 cm diameter, leading from *a* to *a'* and from *b* to *b'*, and so bent that in the heated middle part of the wide tube they run parallel over a length of 30 cm at a distance of only 0.8 cm. In the four openings of the caps, *A* and *B* are fastened air-tight by means of rubber packing. This kind of connection leaves some play, so that by temperature differences

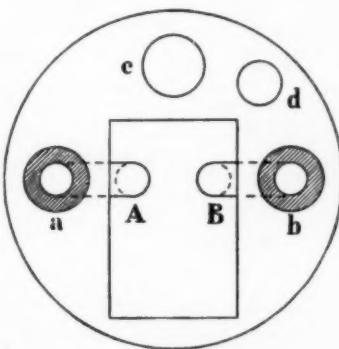


FIG. 2

between the wide and the narrow tubes these latter need not alter their shape through tension. At the same time the rubber insulates *A* and *B* electrically from *NN'*. The four ends of the narrow tubes which project are kept cool by mantles *E* with running water (these are not represented in the figure).



FIG. 3

If an electric current is now passed through *A* or *B*, the temperature of this tube rises a little above that of its surroundings; if an air-current is passed through it, the temperature falls a little below that of its surroundings. The intensities of the currents, and consequently the differences of temperature, can in either case be easily regulated and kept constant for a long time.

Fig. 3 gives a sketch of the whole arrangement. The light of the positive carbon *L* is concentrated by the lens *E* on a screen *Q* having a slit-shaped aperture of adjustable breadth. The lens *F* forms in the plane of the slit *S* of the spectrograph a sharp image of the diaphragm *P*. The optical axis of the two lenses passes through the middle of the tube containing the sodium vapor, exactly between the two small tubes *A* and *B*.

If now the opening in the diaphragm *P* has the shape of a vertical narrow slit, and if its image falls exactly on the slit of the spectrograph, then the continuous spectrum of the arc-light appears with great brightness. If the tube *NN'* is not heated, *D*₁ and *D*₂ are seen as extremely fine dark lines, attributed to absorption by the sodium, which is always present in the neighborhood of the carbons. In order that this phenomenon might always be present in the field of view of the spectrograph as a comparison spectrum, also when the tube is heated, a small totally reflecting prism was placed before part of the slit *S*, to which

part of the principal beam of light was led by a simple combination of lenses and mirrors without passing the electric furnace. Thus the

unmodified spectrum of the source is also seen on each photograph that was taken.

The spectral arrangement used consists of a plane diffraction grating 10 cm in diameter (ruled surface 8 by 5 cm) with 14,436 lines to the inch, and two silvered mirrors of Zeiss; the collimator mirror has a focal length of 150 cm, the other, of 250 cm. Most of the work was done in the second spectrum.

When heating the sodium for the first time a pretty large quantity of gas (according to Wood, hydrogen) escaped from it, which of course was pumped off. After the apparatus had been operated a couple of times, the tension within the tube remained for weeks less than 1 mm of mercury; also during the heating, which, in the experiments described in this paper, never went beyond 450°. The inner wall of NN' , and also the small tubes A and B , are after a short time covered with a layer of condensed sodium, which favors the homogeneous development of the vapor in subsequent heatings. It is remarkable that scarcely any sodium condenses on the parts of the tube that project from the furnace, so that the windows also remain perfectly clear. The density of saturated sodium vapor at temperatures between 368° and 420° has been experimentally determined by F. B. Jewett.¹ He gives the following table:

Temperature	Density	Temperature	Density
368°	0.0000009	395°	0.00000270
373	0.0000020	400	0.00000350
376	0.0000035	406	0.00000480
380	0.0000043	408	0.00000543
385	0.00000103	412	0.00000590
387	0.00000135	418	0.00000714
390	0.00000160	420	0.00000750

These densities are of the same order of magnitude as those of mercury vapor between 70° and 120°. At 387° the density of saturated sodium vapor is about one-thousandth of that of the atmospheric air at 0° and 76 cm.

OBSERVATIONS

If we now regulate the intensity of the current in the furnace in such a manner that the thermo-couple indicates a steady temperature

¹ "A New Method of Determining the Vapor-Density of Metallic Vapors, and an Experimental Application to the Cases of Sodium and Mercury," *Phil. Mag.*, (6) 4, 546, 1902.

(in many of our experiments 390°), then the density of the vapor is not everywhere the same within the tube, for the temperature falls from the middle toward the ends; but since the surfaces of equal temperature are practically perpendicular to the beam of light, all rays pass nearly rectilinearly through the vapor. Accordingly the spectrum is only little changed; the two D lines have become somewhat stronger, which we shall, for the present, ascribe to absorption by the sodium vapor in the tube.

We now blow a feeble current of air through the tube *A*, which thus is slightly cooled, so that sodium condenses on it, the vapor-density in its neighborhood diminishing. We soon see the sodium lines broaden considerably. This cannot be the consequence of increased absorption, since the average vapor-density has decreased a little. The reason is that rays of light with very great refractive indices are now bent toward q' (Fig. 3), and rays with very small indices toward q ; hence in the image of the slit *P* which is formed on *S*, rays belonging to regions on both sides of the D lines no longer occur, while yet this image remains perfectly sharp, since the course of all other rays of the spectrum has not been perceptibly altered. If now at the same time the tube *B* is heated by a current of, say, 20 amperes, by which the density-gradient in the space between the tubes is increased, the breadth of the lines becomes distinctly greater still. The heat generated in the tube by the current is about 1 calorie per second; it is, however, for the greater part conducted away to the cooled ends of the tube, so that the rise of temperature can only be small.

By switching a current key and a cock, *A* and *B* can be made to suddenly exchange parts, so that *A* is heated, *B* cooled. The dark bands then shrink, pass into sharp D lines and then expand again, until, after a few minutes, they have recovered their former breadth.

The lines in the transition stage are fine and sharp, however, only if the temperature of the furnace is very constant. If it rises or sinks, the minimal breadth appears to be not so small. In this case, however, there certainly exist currents in the mass of vapor which cause the distribution of density to be less regular. When, therefore, *A* and *B* being at equal temperatures, we still sometimes see the sodium lines slightly broadened, it stands to reason to attribute this also to refraction in such accidental irregularities.

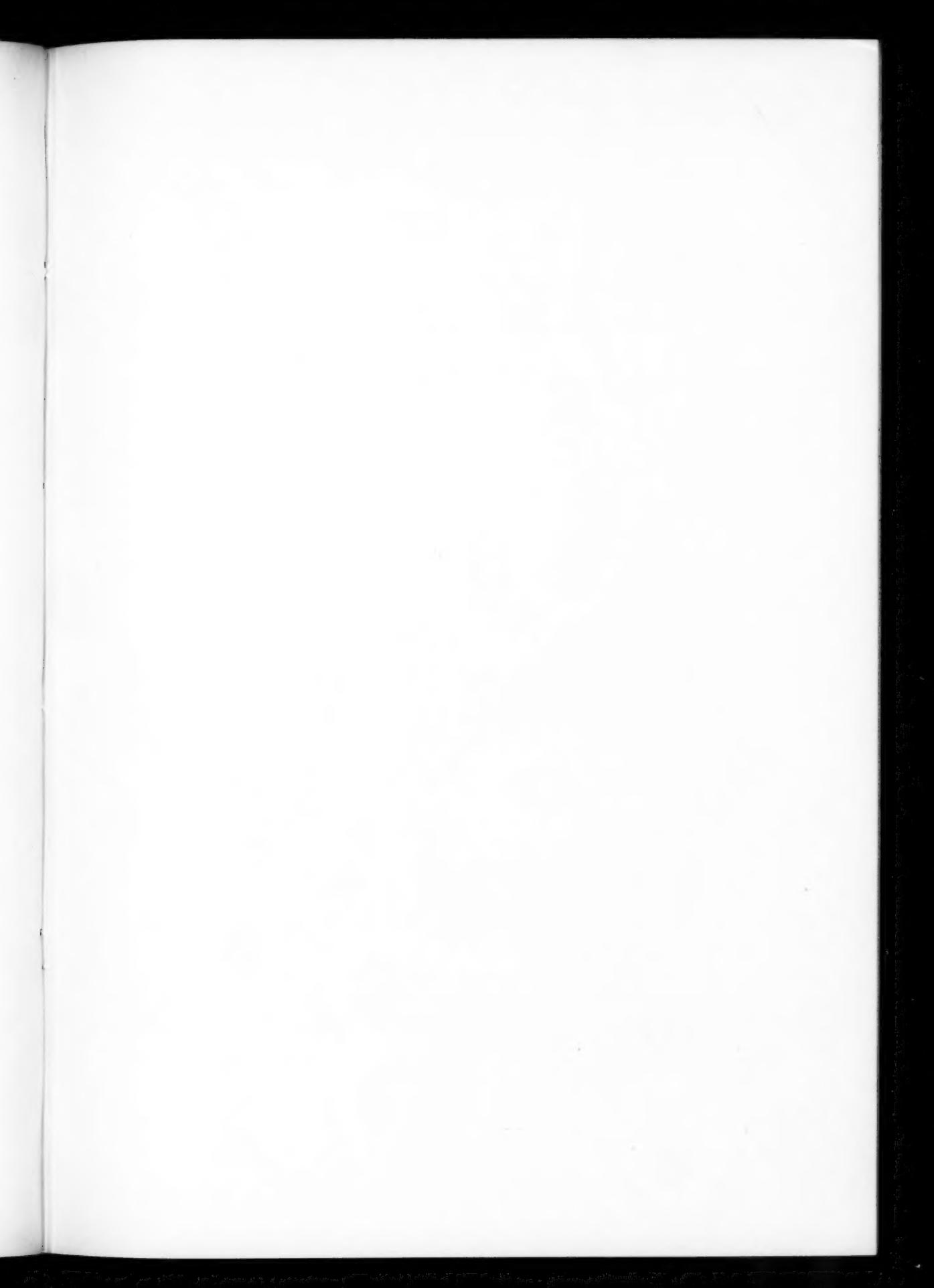
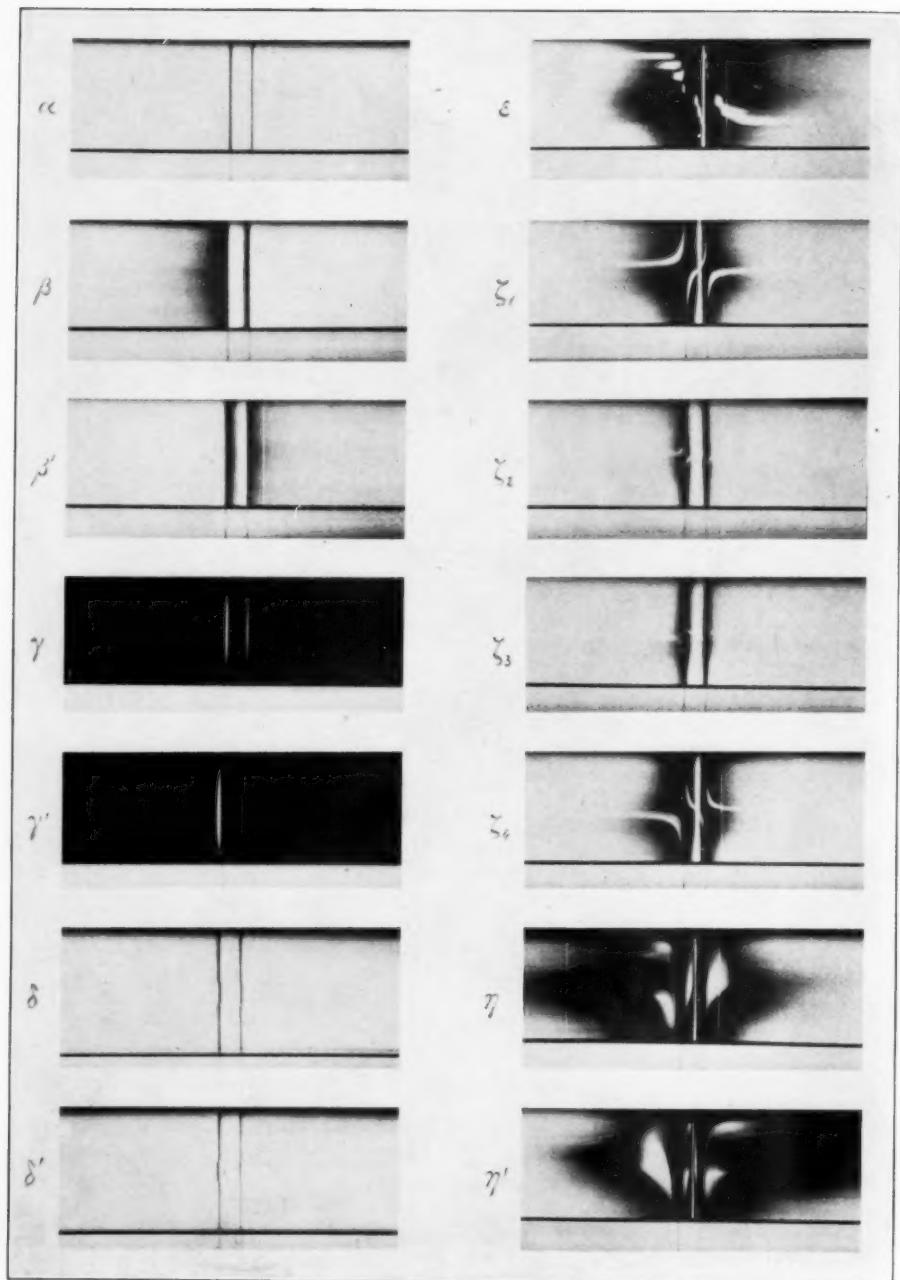


PLATE V



That spectral lines possess some breadth is commonly ascribed either to motion of the light-emitting and absorbing molecules in the line of sight, or to changes in the vibrational period of the electrons by the collisions of the molecules. We now have a third cause—anomalous dispersion in the absorbing medium. The whole series of phenomena observed in our sodium tube corroborates the opinion that this latter cause must in many cases be regarded as by far the most important. It will appear that this conclusion holds not only for dark, but also for bright spectral lines.

If the slit in the diaphragm P is made much broader toward p' , this has no influence on the spectrum as long as A and B are at the surrounding temperature. The D lines appear narrow, as in α , Plate V. If A is now cooled below this temperature, and B is raised above it, the dark D lines broaden only in the direction of the shorter wave-lengths, while at the side of the longer wave-lengths the intensity of the light is even increased. Indeed, the deficiency of these longer waves, which has been observed in the case of the *narrow* slit in P , is now overcompensated by the anomalously bent rays coming from the broad radiating field p' and finding their way through the slit Q to S . The resulting aspect is shown in β on the plate.

The spectrum β passes into β' when the temperature difference between A and B is made to change its sign, or also when the original temperature difference is maintained, but the slit in P is made much wider toward p instead of toward p' ; for with both alterations the rays of longer and those of shorter wave-lengths than D_1 and D_2 , only exchange parts.

A small shifting of the diaphragm P in the direction toward p' (starting from the conditions fulfilled when taking β) brings the image of the screen p upon the slit S , and thus prevents all the light not undergoing anomalous dispersion from reaching S . This causes the spectrum γ to appear, which makes the impression of an emission spectrum of sodium with slightly shifted lines, although it is evidently only due to rays from the field p' which have undergone anomalous dispersion in the vapor.

In a similar way the pseudo-emission spectrum γ' is obtained by shifting the diaphragm a little, starting from the conditions that gave β' .

The cases β and β' may be combined by using a diaphragm P with an opening of the shape of Fig. 4. When the slit S occupies the position of the dotted line in the image of this opening, then, if A is cooled, we shall have the conditions of β in the upper and lower parts of the spectrum, and the conditions of β' in the middle part. The resulting combination of the spectra β and β' may be easily imagined, and has not, therefore, been reproduced. But it is of some interest to notice the appearance of the same combination when the density-

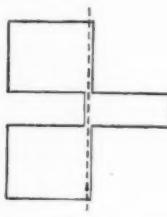


FIG. 4

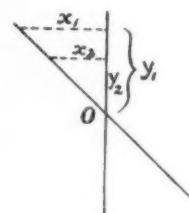


FIG. 5

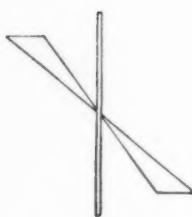


FIG. 6

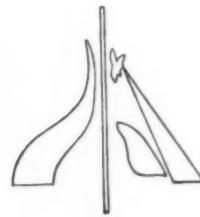


FIG. 7

gradient is made much smaller than it was when taking β and β' ; for now we get δ and, after reversing the gradient, δ' . The line-shifting here produced has, of course, nothing to do with Doppler's principle. The two photographs further prove that even these narrow lines are almost totally due to anomalous dispersion instead of to absorption; indeed, the real, straight absorption line must be common to the three sections, and we see that there is scarcely any room left for it.

(On several of the photographs a few narrow bright lines appear;

they are emission lines of the arc, belong to the extreme violet of the third spectrum, and bear no relation to the phenomena with which we are concerned. The line a little to the right of D, for instance, is probably the calcium line $\lambda 3933.83$, for $3933.83 \times \frac{3}{2} = 5900.74$.)

Let us now return to the diaphragm P with a narrow slit placed in the optical axis. (A piece of glass coated with tin-foil, in which a slit was cut out, was generally used.) The spectrum then shows broad bands when there is a sufficient density-gradient between A and B . If an opening is cut in the tin-foil beside the slit, a group of rays of definite refractivities (and consequently also of definite wavelengths) is given an opportunity to reach S through Q , and a bright spot is formed in the dark band, the shape of which depends on the shape of the opening in the tin foil, but is by no means identical with it. Thus, for instance, the spectrum ϵ shows the effect of a series of rectangular openings in the screens p and p' .

The law connecting the form of bright areas in the dispersion bands with the shape of openings in the screen is not very simple, because it depends on the configuration of the surfaces of equal density in the space between the tubes A and B . Some idea of the connection may be got if we simplify the problem by supposing those surfaces to be parallel planes, perpendicular to the plane containing the axes of A and B . The latter plane may cut the slit P in the point O and the slit S in O' . We shall take O as the origin of rectangular co-ordinates x (horizontal) and y (vertical), by which the points in the plane of the screens p and p' may be determined. Points in the image on S may be designated by x' and y' with respect to O' .

Now let us suppose a pin-hole xy to be made in p' . Light coming from this point will be focused by the lens F at a point $x'y'$ beside the slit S , provided it has not deviated in the sodium vapor. It does not get into the spectrograph. But the rays undergoing anomalous dispersion will spread out nearly horizontally; the lens F unites them in a continuous series of points having about the same y' , but various values of x' . Only those for which $x'=0$ enter into the spectrograph. If in the spectrum the middle of one of the sodium lines be called O'' , the co-ordinates of the bright spot, produced in the dark dispersion band by the beam that entered, will be y'' (pro-

portional to y') and z , the abscissa z depending on the wave-length λ of that beam.

The connection between this wave-length and the abscissa x of the hole is given by the dispersion-curve of the sodium vapor. Indeed, we can easily prove that x is proportional to $n - 1$, the factor only depending on linear dimensions of the arrangement, and on the density-gradient of the vapor.¹ So, for a given x , n may be computed; the corresponding λ is taken from the dispersion curve, and in the spectrum we have $z = \lambda - \lambda_D$. The ordinate y'' is derived from y by merely introducing focal distances. We shall thus have expressed the co-ordinates of the bright spot in terms of the co-ordinates of the pin-hole.

The following instance may serve to elucidate the connection between corresponding figures in the plane P and in the spectrum, without calculation.

Instead of the pin-hole we make a second straight slit in the diaphragm, cutting the first one obliquely in O (Fig. 5). Now all positive and negative values of x , and therefore of $n - 1$, are represented each of them belonging to a separate value of y which is proportional to it:

$$y_1 : y_2 = x_1 : x_2 = (n_1 - 1) : (n_2 - 1).$$

As the ordinates y'' in the spectrum are proportional to y , we have also

$$y''_1 : y''_2 = (n_1 - 1) : (n_2 - 1).$$

At the same time

$$z_1 : z_2 = (\lambda_1 - \lambda_D) : (\lambda_2 - \lambda_D).$$

The bright curve in the spectrum, therefore, is the dispersion-curve itself, with the point $n = 1$, $\lambda = \lambda_D$ taken for the origin of co-ordinates.

The spectrum ζ_1 of Plate V realizes this case. It has been obtained by using a diaphragm with an opening of the shape of Fig. 6. The width of the oblique slit was enlarged toward the ends in order to increase the luminosity of the ascending and descending branches of

¹ From the equations (1) and (2) on pages 106 and 107 follows immediately

$$x = dlR \frac{d\Delta}{ds} = dl \frac{d\Delta}{ds} \cdot \frac{1}{\Delta} (n - 1).$$

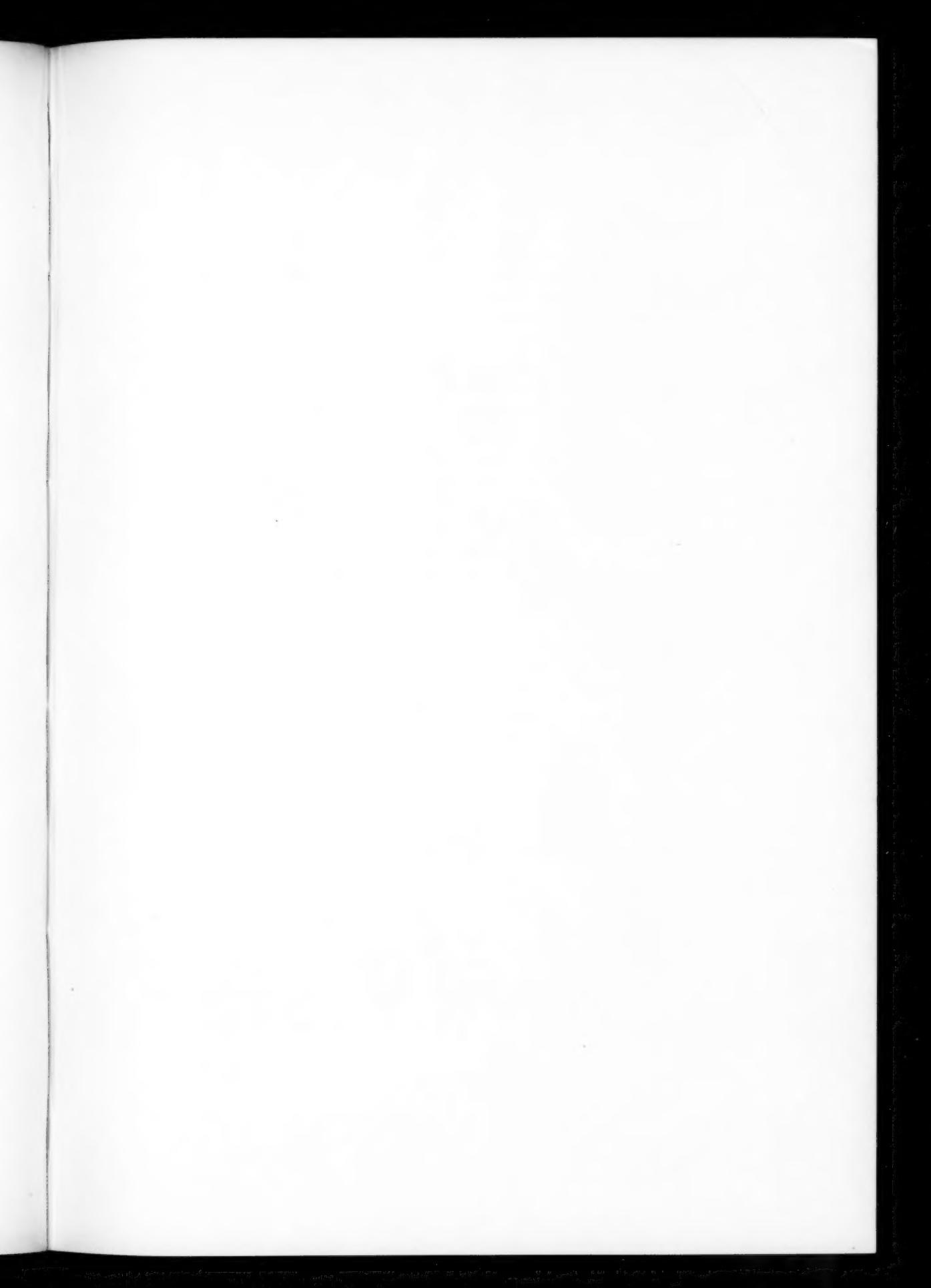
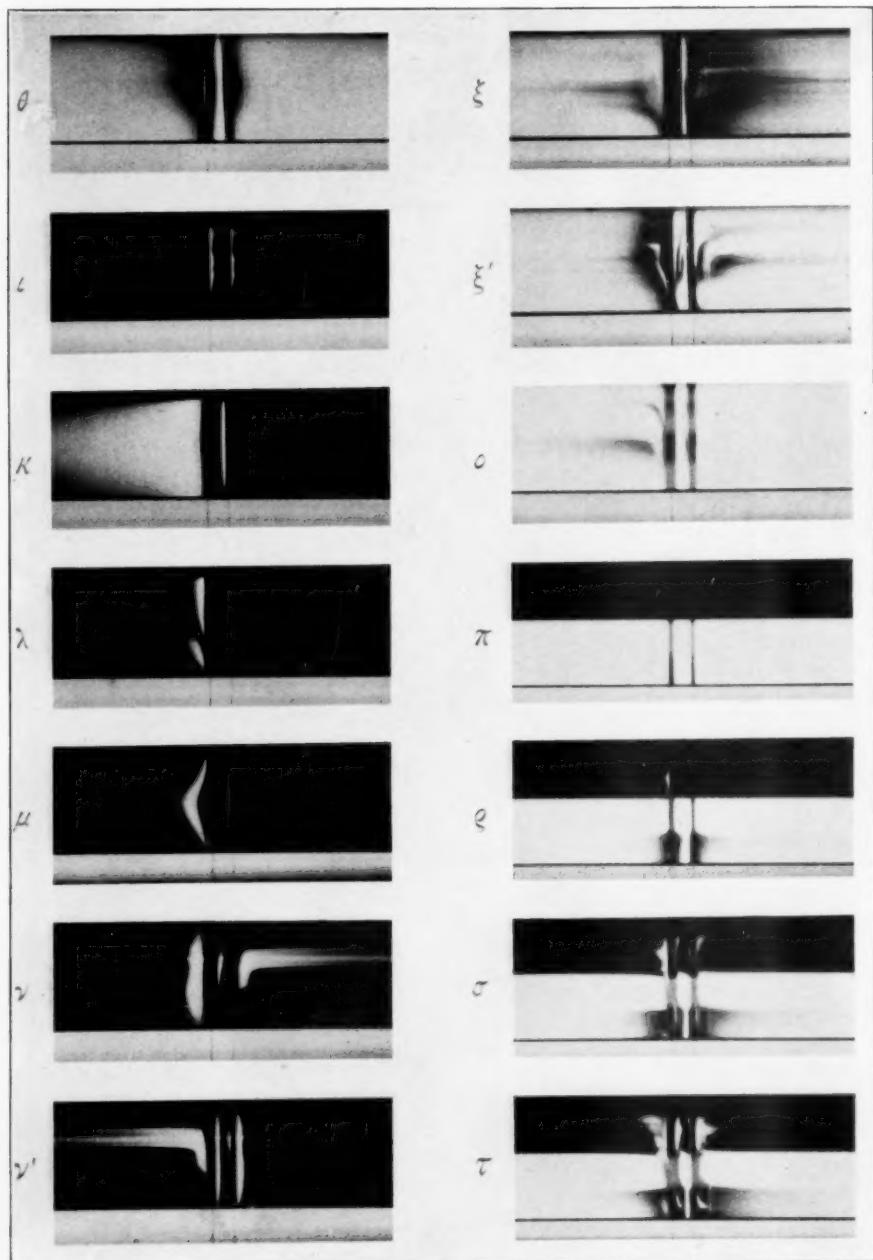


PLATE VI



the curve. When the electric current and the air current through the tubes are diminished, the figure shrinks to ζ_2 ; when they are stopped, we return to a ; reversing the gradient makes the spectrum proceed through ζ_3 to ζ_4 .

Having thus experimentally found the relation between the two figures for a simple case, it is not difficult to design for any desired distribution of light the shape of the required opening in the diaphragm. The flower η , for instance, requires the diaphragm represented in Fig. 7; by reversing the gradient the image η passes into η' .

Thus we possess the means for arbitrarily producing all stages of enhancement, wingedness, reversal, shifting, duplication, ramification of bright or dark spectral lines, and it seems possible faithfully to reproduce all phenomena observed in this respect in the spectra of sun-spots, faculae, flocculi, or prominences. On Plate VI a number of arbitrary distributions of light have been collected. They were all produced in sodium vapor of 390° on the average. In θ on the dark dispersion band D_2 a bright double line is seen, reminding us of the spectrum of the calcium flocculi described by Hale. In the same negative D_1 also shows a fine double line which, I fear, will be invisible in the reproduction. The spectrum ι is not unlike that of a prominence taken with the tangential slit; κ reminds us of certain star spectra; etc. The photographs π , ρ , σ imitate the development of a prominence and a sun-spot spectrum: π represents the spectrum of the quiet solar limb with radially placed slit; in ρ a prominence appears and a spot with phenomena of reversal; σ shows all of this in a stronger degree. If now the density-gradient is made to change sign, the image first shrinks again to π , after which it expands to τ , in a certain sense the inversion of σ .

The striking spectacle of these phenomena, the gradual changes of which admit of perfect control, is only poorly reproduced by the photographs.

Plate VII shows on a slightly larger scale some photographs taken in the third spectrum with sodium vapor of only 320° . The density of the saturated vapor at this temperature is unknown. If the temperature-density-curve found by Jewett is extended beyond the observations so as to be in harmony with the shape of the better-known curve of mercury, we may infer that at 320° the density will

probably be inferior to 0.0000003. The density-gradient produced by cooling or heating our tubes must have been of the order of magnitude 0.0000001 in these experiments. The diaphragm used was the same as that which served with δ and δ' . When taking v and ϕ , the slit S occupied the position of the dotted line in the image of the opening, Fig. 4; with χ the slit was a little to the left; with ψ and ω a little to the right. We see from these photographs that the real absorption lines of the sodium vapor must have been excessively narrow; indeed, it is dubious whether they can be distinguished at all and the distribution of the light seems to be wholly governed by anomalous dispersion.

THE RELATION BETWEEN THE CURVATURE OF THE RAYS AND THE DENSITY-GRADIENT

The question arises whether it is *probable* that circumstances such as were realized in our experiments are also met with in nature, or in ordinary spectroscopical investigations undertaken with entirely different purposes.

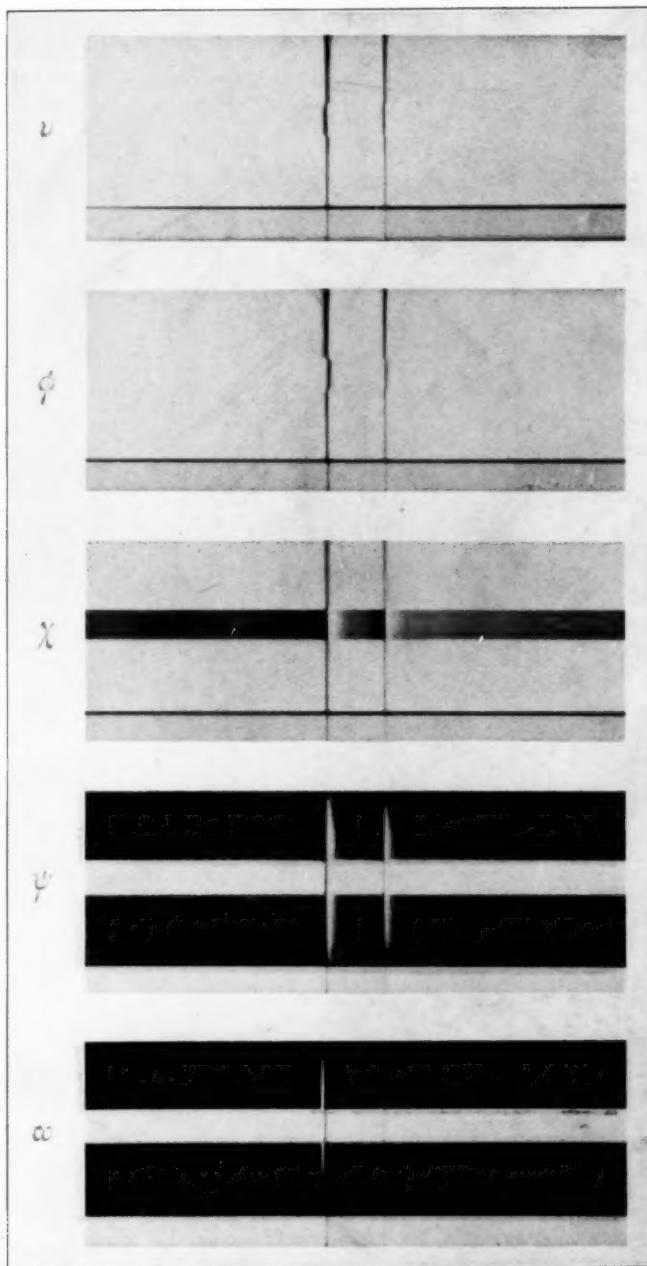
We remark, in the first place, that curiously shaped diaphragm openings are not absolutely essential for the production of phenomena as those described above. If, for instance, our source of light had a constant, say circular, shape; if, on the other hand, the direction and magnitude of the density-gradient in our tube had not been so regular, but very different in various places of the field reproduced by the lens F , then the D lines would also have shown all sorts of excrescences, now determined by the configuration of the density distribution.

In the second place, we will try to form some idea of the quantitative relations.

The radius of curvature ρ of the path of the most deviated rays occurring in our photographs may be easily estimated from the distance d of the diaphragm to the middle of the furnace, the distance x of one of the most distant diaphragm openings to the optical axis, and the length l of the space in which the incurvation of the rays is brought about. For

$$\rho : l = d : x. \quad (1)$$

PLATE VII



Putting $x=1$ cm, $d=110$ cm, $l=27$ cm, this gives $\rho=3000$ cm. The average density Δ of the sodium vapor was in this case about one one-thousandth of that of the atmospheric air.

Let us see how ρ changes with the density-gradient. We always have

$$\rho = \frac{n}{n'}$$

if n represents the local index of refraction of the medium for the ray under consideration and $n' = \frac{dn}{ds}$ the change of this index per centimeter in the direction of the center of curvature. We have approximately for a given kind of light

$$\frac{n-1}{\Delta} = \text{constant} = R,$$

$$\eta = R\Delta + 1,$$

$$n' = \frac{dn}{ds} = R \frac{d\Delta}{ds}.$$

From this follows

$$\rho = \frac{R\Delta + 1}{R \frac{d\Delta}{ds}};$$

but since for rarefied gases n differs little from unity, even for the anomalously dispersed rays which we consider, $R\Delta$ may be neglected with regard to 1 and we may write

$$\rho = \frac{1}{R \frac{d\Delta}{ds}}. \quad (2)$$

For every kind of light ρ is consequently inversely proportional to the density-gradient of the vapor in the direction perpendicular to that of propagation.

An estimate of the magnitude of the density-gradient existing, in our experiments, between A and B may be obtained in two ways. It may be inferred either from the difference of temperature produced, or from formula (2). The temperature difference between A and B would have been pretty easy to determine thermo-electrically; up to the present, however, I have had no opportunity to make the

necessary arrangement. Besides, the relation between the density distribution in the space traversed by the rays, and the temperatures of *A* and *B*, cannot be so very simple, since we have to deal, not with two parallel planes, but with tubes, from which, moreover, many drops of liquid sodium hang.

The second method at once gives an average value of $\frac{d\Delta}{ds}$ for the space traversed by the rays. It requires a knowledge of $R = \frac{n-1}{\Delta}$ for a kind of ray for which in our experiments also ρ has been determined.

Now, Wood¹ gives a table for the values of *n* for rays from the immediate vicinity of the D lines. These data, however, refer to saturated sodium vapor of 644°; but we may deduce from them the values of *n* for vapor of 390° by means of the table which he gives in his paper on page 317.

For, when we heat from 390° to 508°, the refractive power of the vapor (measured by the number of passing interference fringes of helium light $\lambda=5875$) becomes $\frac{9.8}{9} = 11$ times greater, and at further heating from 506° to 644° again $\frac{5.0}{4} = 12.5$ times greater (now found by interference measurement with light from the mercury line $\lambda=5461$); hence from 390° to 644° the refractive power increases in ratio of 1 to $11 \times 12.5 = 137$.

Since now for rays situated at 0.4 Ångström unit from the D lines² we have $n-1 = \pm 0.36$ (as the average of three values taken from Wood's table on page 319), we ought to have with sodium vapor at 390° for the same kind of rays

$$n-1 = \frac{0.36}{137} = 0.0026 .$$

The density Δ at 390° is, according to Jewett, 0.0000016, whence

$$R = \frac{n-1}{\Delta} = \frac{0.0026}{0.0000016} = 1600 .$$

¹ *Phil. Mag.*, (6) **8**, 319, 1904.

² The spectrum ξ_1 in our plate shows that the extremities of the peaks correspond pretty well to light of this wave-length; for they approach the D lines to a distance which certainly is no more than one-fifteenth of the distance of the D lines which amounts to 6 Ångström units. For these rays the opening of the diaphragm was 1 cm distant from the optical axis.

Then from formula (2) follows

$$\frac{d\Delta}{ds} = \frac{1}{R\rho} = \frac{1}{1600 \times 3000} = 0.0000002.$$

DISPERSION BANDS IN THE SPECTRA OF TERRESTRIAL SOURCES

It is very probable that, when metals evaporate in the electric arc, values of the density-gradient are found in the neighborhood of the carbons that are more than a thousand times greater than the feeble density-gradient in our tube with rarefied sodium vapor.¹

The radius of curvature will, therefore, in these cases be over a thousand times smaller than 30 meters, and so may be no more than a few centimeters or even less. A short path through the vapor mass is then already sufficient to alter the direction of certain rays very perceptibly.

If now an image of the carbon points is produced on the slit of a spectroscope, then this is a *pure* image only as far as it is formed by rays that have been little refracted in the arc, but the rays which undergo anomalous dispersion do not contribute to it. Light of this latter kind, coming from the crater, may be lacking in the image of the crater, and, on the other hand, penetrate the slit between the images of the carbon points. Thus, in ordinary spectroscopic observations, broadening, not only of absorption lines, but also of emission lines, must often to a considerable extent be attributed to anomalous dispersion.

When we bear this in mind, many until now mysterious phenomena will find a ready explanation. So, for instance, the fact that Liveing and Dewar² saw the sodium lines strongly broadened each time when vapor was vividly developed after bringing in fresh material, but saw them become narrower again when the mass came to rest, although the density of the vapor did not diminish. If by pumping nitrogen into the evaporated space the pressure was gradu-

¹ If, for instance, we put the vapor-density of the metal in the crater, where it boils, at 0.001, the density of the vapor outside the arc at a distance of 1 cm from the crater at 0.00001, then we have already an average gradient 5000 times as large as that used in our experiments.

² "On the Reversal of the Lines of Metallic Vapors," *Proc. R. S.*, 27, 132-136; 28, 367-372, 1878-1879.

ally increased, the lines remained sharp; but if the pressure was suddenly released, they were broadened. All this becomes clear as soon as one has recognized in the lines dispersion bands, which must be broad when the density of the absorbing vapor is irregular, but narrow, even with dense vapor, if only the vapor is evenly spread through the space.

Another instance. According to the investigations of Kayser and Runge, the lines belonging to the second secondary series in the spectra of magnesium, calcium, cadmium, zinc, mercury, are always hazy toward the red and are sharply bordered toward the violet; whereas lines belonging to the first secondary series or to other series are often distinctly more widened toward the violet. With regard to the spectrum of magnesium they say:

Auffallend ist bei mehreren Linien, die wir nach Roth verbreitert gefunden haben, dass sie im ROWLAND'schen Atlas ganz scharf sind, und dann stets etwas kleinere Wellenlänge haben. So haben wir 4703.33, ROWLAND 4703.17; wir 5528.75, ROWLAND 5528.62. Unschärfe nach Roth verleiht ja leicht der Linie grössere Wellenlänge zuzuschreiben; so gross kann aber der Fehler nicht sein, denn die ROWLAND'sche Ablesung liegt ganz ausserhalb des Randes unserer Linie. Wir wissen daher nicht, woher diese Differenz röhrt.¹

Kayser has later² given an explanation of this fact, based on a combination of reversal with asymmetrical widening; but a more probable solution is, in my opinion, obtained when we regard the widened serial lines partly as dispersion bands.

If we assume that, when we proceed from the positive carbon point, which emits the brightest light, to the middle of the arc, the number of the particles associated with the second secondary series decreases, then rays coming from the crater, whose wave-length is slightly greater than that of the said serial lines, will be curved so as to turn their concave side to the carbon point. Their origin is erroneously supposed to be in the prolongation of their final direction, so they seem to come from the arc, and we believe we see light emitted by the vapor, in which light different wave-lengths occur, all greater than the exact wave-length of the serial lines. The observed displaced lines of the second secondary series are consequently comparable to apparent emission lines of the spectrum γ of Plate V.

¹ Kayser und Runge, *Über die Spektren der Elemente*, 4, 13.

² Kayser, *Handbuch der Spektroskopie*, 2, 366.

In this explanation things have been represented as if the light of these serial lines had to be *exclusively* attributed to anomalous dispersion. Probably, however, in the majority of cases, emission proper will indeed perceptibly contribute to the formation of the line; the sharp edge must then appear in the exact place belonging to the particular wave-length.

How can we now explain that lines of other series are diffuse at the opposite side? Also this may perhaps be explained as the result of anomalous dispersion, if we assume that of the emission centers of these other series the density *increases* when we move away from the positive carbon point. In this case, namely, the rays originating in the crater, which are concave toward the carbon point and consequently seem to come from the arc, possess shorter wave-lengths than the serial lines; i. e., the serial lines appear widened toward the violet. This supposition is not unlikely. For the positive and negative atomic ions which, according to Stark's theory, are formed in the arc by the impact of negative electronic ions, move in opposite directions under the influence of the electric field; hence the density-gradients will have opposite signs for the two kinds. Series whose lines are diffuse toward the red, and series whose lines flow out toward the violet, would, according to this conception, belong to, or be produced by, ions of opposite signs—a conclusion which at all events deserves nearer investigation.

The examples given may suffice to show that it is necessary systematically to investigate to what extent the already known spectral phenomena may be the result of anomalous dispersion. A number of cases in which the hitherto neglected principle of ray-curving has undoubtedly been at the root of the matter are found in Kayser's handbook, 2, 292–298, 304, 306, 348–351, 359–361, 366.

DISPERSION BANDS IN THE SPECTRA OF CELESTIAL BODIES

Since almost any peculiarity in the appearance of spectral lines may be explained by anomalous dispersion, if only we are at liberty to assume the required density distributions, we must ask, when applying this principle to astrophysical phenomena: Can the values of the density-gradient for the different absorbing gases in celestial bodies really be such that the rays are sufficiently curved to exert

such a distinct influence on the distribution of light in the spectrum?

In former communications¹ I showed that the sun, for instance, may be conceived as a gaseous body, the constituents of which are intimately mixed, since all luminous phenomena giving the impression as if the substances occurring in the sun were separated, may be brought about in such a gaseous mixture by anomalous dispersion. We will now try to prove, not only that this *may* be the case, but that it *must* be so on account of the most likely distribution of density.

Let us put the density of our atmosphere at the surface of the earth at 0.001293. At a height of 1050 cm it is smaller by $\frac{1}{760}$ of this amount, so that the vertical density gradient is

$$\frac{0.001293}{1050 \times 760} = 16 \times 10^{-10}.$$

The horizontal gradients occurring in the vicinity of depressions are much smaller; even during storms they are only about one one-thousandth of the said value.² Over small distances the density-gradient in the atmosphere may of course occasionally be larger, through local heating or other causes.

Similar considerations applied to the sun, *mutatis mutandis*, cannot, however, lead to a reliable estimate of the density-gradients there occurring. A principal reason why this is for the present impossible is found in our inadequate knowledge of the magnitude of the influence, exerted by *radiation-pressure* on the distribution of matter in the sun. If there were no radiation-pressure, we might presuppose, as is always done, that at the level of the photosphere gravitation is twenty-eight times as great as on the earth; but it is counteracted by radiation-pressure to a degree, dependent on the size of the particles; for some particles it may even be entirely abolished. The radial density-gradient must, therefore, in any case be much smaller than one might be inclined to calculate on the basis of gravitational action only.

¹ *Proc. Roy. Academy Amsterdam*, 2, 575; 4, 195; 5, 162, 589, and 662; 6, 270; 8, 134, 140, and 323. *Astrophysical Journal*, 12, 185-200; 15, 28-37; 18, 50-64; 21, 271-291. *Physikalische Zeitschrift*, 4, 85-90; 132-136; 6, 239-248. A sketch of a solar theory, in which refraction and dispersion have been considered, is to be found in the *Revue générale de sciences*, 15, 480-495, 1904.

² Arrhenius, *Lehrbuch der kosmischen Physik*, p. 676.

Fortunately we possess another means for determining the radial density-gradient in the photosphere, at any rate as far as the order of magnitude is concerned. According to Schmidt's theory, the photosphere is nothing but a critical sphere the radius of which is equal to the radius of curvature of luminous rays whose path is horizontal at a point of its surface. This radius of curvature is consequently $\rho = 7 \times 10^{10}$ cm, a value which we may introduce into the expression for the density-gradient:

$$\frac{d\Delta}{ds} = \frac{1}{R\rho}.$$

The refractive equivalent R for rays that undergo no anomalous dispersion varies with different substances, to be sure; but in an approximate calculation we may put $R=0.5$. Then at the height of the critical sphere we shall have

$$\frac{d\Delta}{ds} = \frac{1}{0.5 \times 7 \times 10^{10}} = 0.29 \times 10^{-10},$$

(this is 50 times less than the density-gradient in our atmosphere). All arguments supporting Schmidt's explanation of the sun's limb are at the same time in favor of this estimate of the radial density-gradient in the gaseous mixture. It should be observed, on the other hand, that, when things are considered from other points of view than from Schmidt's theory, this density-gradient appears by no means improbably large. Yet gradients of this order of magnitude will produce ray-curving in a degree amply sufficient for giving rise to very conspicuous dispersion phenomena, as we shall see presently. If, therefore, arguments are found for assuming larger density-gradients, our explanations will thereby only be corroborated.

Let us now consider rays that do undergo anomalous dispersion. In order that light, the wave-length of which differs but very little from that of one of the sodium lines, may seem to come from points situated some seconds of arc outside the sun's limb, the radius of curvature of such anomalously bent rays need only be slightly smaller than 3×10^{10} cm. Let us put, for instance,

$$\rho' = 6 \times 10^{10} \text{ cm}.$$

If we further assume that of the kind of light under consideration the wave-length is 0.4 Ångström units greater than that of D_1 , then

for this kind of light $R' = 1600$, as may be derived from the observations of Wood and of Jewett;¹ we thus find for the density-gradient of the sodium vapor,

$$\frac{d\Delta'}{ds} = \frac{1}{R'\rho'} = \frac{1}{1600 \times 6 \times 10^{10}} = 0.0001 \times 10^{-10},$$

a quantity 2900 times smaller than the density-gradient of the gaseous mixture.

Hence if only one three-thousandth part of the gaseous mixture consists of sodium vapor, then, on account of the assumed radial density-gradient of the mixture, the critical sphere (or the photosphere) will already seem to be surrounded by a "chromosphere" of light, this light having a striking resemblance with sodium light. This kind of light has, so to say, its own critical sphere which is larger than the critical sphere of the light not anomalously refracted. If the percentage of sodium were larger, the "sodium chromosphere" would appear higher.

It is customary to draw conclusions from the size of the chromospheric and flash crescents, observed during a total eclipse with the prismatic camera, as to the *height* to which various vapors occur in the solar atmosphere. According to us, this is an unjustified conclusion. On the other hand, it will be possible to derive from these observations data concerning the *ratio in which these substances are present in the gaseous mixture*, provided that the dispersion-curves of the metallic vapors, at known densities, shall first have been investigated in the laboratory.

Until now we have dealt only with the normal radial density-gradient. By convection and vortex motion, however, irregularities in the density distribution arise, with gradients of various direction and magnitude. And since on the sun the resultant of gravitation and radiation-pressure is relatively small, there the irregular density-gradients may reach values that approach the radial gradient sooner than on the earth, or may be occasionally larger.

The incurvation of the rays in these irregularities must produce capriciously shaped sodium prominences, the size of which depends, among other causes, on the percentage of sodium vapor in the gaseous mixture.

So the large hydrogen and calcium prominences prove that rela-

¹ See page 108.

tively much hydrogen and calcium vapor is present in the outer parts of the sun; but perhaps even an amount of a few per cent. would already suffice to account for the phenomena.¹

If we justly supposed that non-radially directed density-gradients are of frequent occurrence in the sun, and there disturb the general radial gradient much more than on the earth, then not only rays from the marginal region, but also rays from the other parts of the solar disk, must sensibly deviate from the straight line. Chiefly concerned are, of course, the rays that undergo anomalous dispersion. *Every absorption line of the solar spectrum must consequently be enveloped in a dispersion band.*

To be sure, absorption lines of elements which in the gaseous mixture occur only in a highly rarefied condition, present themselves as almost sharp lines, since for these substances all density-gradients are much smaller than for the chief constituents, and so the curvature of the rays from the vicinity of these lines becomes imperceptible. Also some lines of strongly represented elements may appear sharp, since not all lines of the same element, with given density, cause anomalous dispersion in the same degree. Perhaps there are even absorption lines which under no condition give rise to this phenomenon; though this would be rather improbable from the point of view of the theory of light.

Be this as it may, the limitations mentioned do not invalidate our principal conclusion: that the general interpretation of the solar spectrum has to be modified. We are obliged to see in Fraunhofer's lines not only absorption lines, as Kirchhoff does, but chiefly dispersion bands (or dispersion lines). And that refraction has a preponderant influence also on the distribution of light in stellar spectra cannot be doubted either.

We must become familiar with the idea that in the neighborhood of the celestial bodies the rays of light are in general curved, and that consequently the whole interstellar space is filled with *nonhomogeneous radiation fields*² of different structure for the various kinds of light.

¹ This result would be in accordance with a hypothesis of Schmidt (*Physikalische Zeitschrift*, 4, 232 and 341), according to which the chief constituent of the solar atmosphere would be a very light gas, until now unknown.

² "Das ungleichmässige Strahlungsfeld und die Dispersionsbanden," *Physikalische Zeitschrift*, 6, 239-248, 1905.

STUDIES IN SENSITOMETRY I.
THE DAYLIGHT SENSITOMETRY OF PHOTOGRAPHIC PLATES,
AND A SUGGESTED STANDARD DISPERSION-PIECE

BY ROBERT JAMES WALLACE

INTRODUCTORY

The universal adaptation of the modern dry plate, and the varying demands which are made upon its service, have resulted in an increase of knowledge relative to the imperfections of the photographic plate as a means of recording anything save the actual form of the object photographed. In many cases even that is doubtful. These imperfections have compelled the "testing" of the various plates by many individuals, the object of such tests being principally the determination of the relative color-sensitiveness and comparative speed.

Many methods have been suggested for this purpose, the enumeration of which needs find no place here. It is sufficient to say that methods depending for their results upon the use of colored glasses and pigments are now generally recognized as incomplete, and as leading to erroneous conclusions where the work is in any degree quantitative. What one desires to know is the sensitiveness of the plate to pure color, not admixture, because, if one knows this sensitiveness, it is a comparatively easy matter to calculate the action of mixtures. For example, a patch of red-pigment-stained paper may be photographed, and a strong impression of the same developed upon a plate; but it does not follow that, because such an impression is obtained, the plate is "red-sensitive." For although the patch reflects red, it also, in less degree, reflects all other hues of the spectrum; and the developed impression is just as likely to be due to the combined action of such other hues, as to the red, when we take into consideration the fact that the plate is relatively many times more sensitive to those hues which are secondary in reflection.

Discarding these various makeshifts, a great number of photographic workers have of late acquired various forms and types of spectrometers, and have literally flooded the journals devoted to that

subject with all sorts and conditions of spectra. This, while to be welcomed as a move in the right direction, is yet liable to give rise to many very grave errors in interpretation. The gravity of these errors has been commented upon by sundry writers at various times, and a brief notice was given to the subject by the present writer in a former paper.¹ It may, however, contribute to the clearness of this whole subject if such errors are described here at somewhat greater length.

The possession of a "spectroscope" does not imply results of value unless its possessor understands his instrument, and is acquainted with the laws of light and color. Much excellent material is readily available, and there is little excuse for the heterogeneous results which are unhappily so common in photography, in which almost every worker appears to be a law unto himself.

The three constants which govern the definition of color are hue, purity, and luminosity. By "hue" is meant what is ordinarily termed "color;" for when we speak of an object as having such and such a color, we are referring to its hue. The next constant, purity, concerns the admixture of the color with other colors, or with white light; while luminosity refers to the brightness of the hue under consideration. Of these three constants the photographic plate is chiefly concerned with the last.

The entire value of the spectrum for this class of investigative work lies in the fact that in it we obtain a standard of pure color, from the verdict of which there is no appeal, and to which everything colored must inevitably be referred. But there are many widely different forms of spectrosopes available, from the small direct-vision prismatic instruments to the concave diffraction grating, each of which has its own particular value for different lines of work, but which are, generally speaking, ill suited for sensitometric work in pure photography.

PRISMATIC AND DIFFRACTION SPECTRA

First dividing the subject into its two great classes of prismatic and diffraction spectra, let us consider each separately. In the first instance we are dealing with a spectrum formed by the passage of light through a prism (or prisms), as the name implies. In the

¹ *Astrophysical Journal*, 22, 153, 1905, and 24, 268, 1906.

direct-vision instrument, of which the Browning may be taken as a type, we have an element of dense flint glass combined with an element of crown glass. In instruments of angular deviation type, we have generally an element of flint glass alone, used on account of the greater dispersion obtainable from a glass of comparatively high refractive index. In all prismatic spectra the error arising from irrationality is the most readily noticeable. The abnormality in the hues by reason of the unequal distribution of intensity (luminosity) is not so apparent, however, although rendering the results by one prism not comparable with those from another. A very serious cause of error lies in the fact that the absorption of the glass composing the prism has a strong influence upon the results; generally speaking, the higher the refractive index of the glass employed, the greater the absorption. Again, two prisms of identical refractive index may give photographic results diametrically opposite to each other, because of varying absorption in the prisms themselves, aside from density; for example, two prisms could have identical refractive indices, and yet one be composed of colorless glass, while the other was composed of gray or blue glass.

CONVERSION FORMULAE

Various formulae have been advanced from time to time, designed to bring those discordant results into harmony with one another; but unfortunately they do not satisfy the conditions demanded in quantitative plate-testing. They are all principally concerned with the dispersion of the spectrum, and not with its relative luminosity. What one wants to know is not merely whether or not a plate is sensitive to red, but in what degree that sensitiveness exists. All plates are sensitive to the least refrangible hues, if they get sufficient exposure, but that plate which requires relatively the shortest exposure, other things being equal, is the best plate for work in that region; or, in other words, that plate which will show the greatest extent of the spectrum with normal exposure is the best plate for all round work.

The formula most commonly in use by photographic workers is $\frac{a}{b}m=n$, where a = prismatic dispersion, b = normal dispersion, m =

density of prismatic spectrum, and n =density of normal spectrum; hence $am=bn$.

In order that we may clearly understand the value of this formula, measurement was made of the prismatic spectrum ($\mu_D = 1.6994$) shown in Fig. 1a (Plate VIII) and its curve plotted in the usual manner (Fig. 2). A wave-length scale being then prepared, this curve was reduced by means of the above formula, the result of which is shown in Fig. 3, a. On the same scale are plotted the measurements from a spectrum

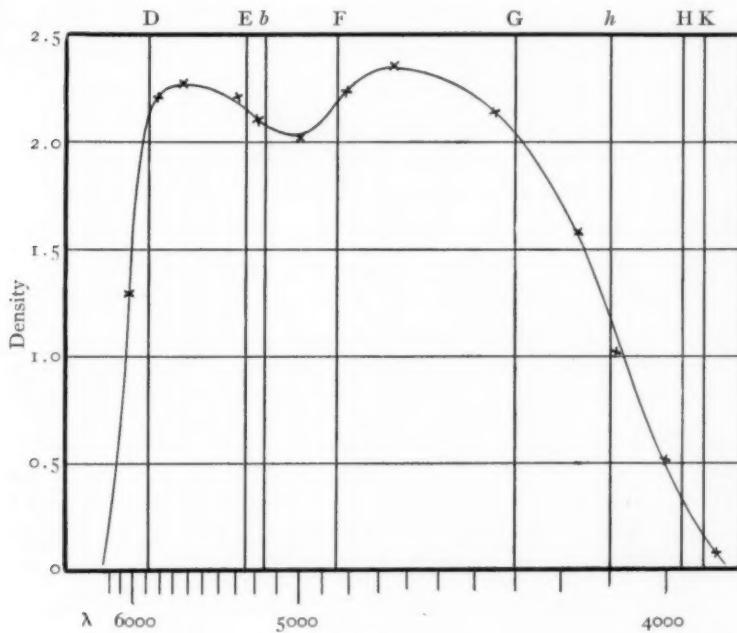


FIG. 2

negative obtained by a replica-grating upon a similar plate, the value of whose region of highest density was practically identical with that of the reconstructed curve of the prismatic spectrum. The woeful lack of agreement is strongly in evidence. Not only is the reconstructed curve deficient in the ultra-violet, but the maximum of sensitiveness is seen to be shifted bodily toward the red end. Further words are unnecessary on this point. What is wanted is a formula which will take into consideration the loss in luminosity by absorption

and the shift due to density of the material used in the construction of the prism.¹

REFLECTION DIFFRACTION GRATING

Turning now to diffraction spectra, it is well known that the speculum metal on which the original grating is ruled possesses in itself a selective absorption which again varies with different "meltings," and which influences the distribution of color-intensity throughout the spectrum. As the grating ages it becomes tarnished by exposure

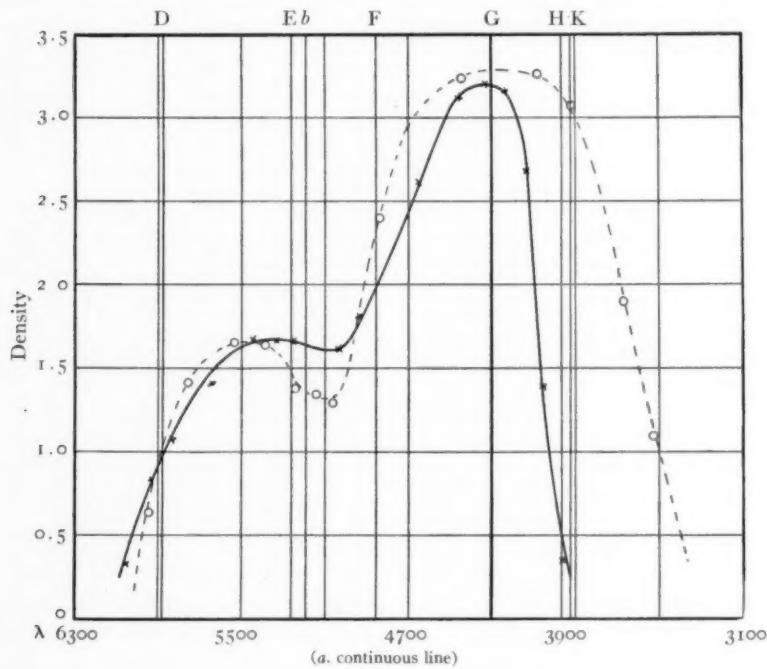


FIG. 3

to the air and the various fumes of the laboratory, and this tarnish is in itself a strong factor in unequal color distribution. Again, the nature of the groove made by the cutting diamond not only determines the distribution of spectral intensity, but influences also the luminosity of the individual hue, amounting in exceptional cases even to abnormality, so that the spectra of no two gratings are defi-

¹ A search for a formula fulfilling the requirements specified is now in progress with prospect of a successful result.

nitely comparable one with the other, in so far as spectral luminosity is concerned.

REPLICA-GRATING

It may be objected that several of the complaints just cited do not amount to much in practical photographic sensitometry. Granted that this is so, they are disadvantages and have been treated as such. Not all have been mentioned, however, but merely *those which can be remedied by the adoption of the replica-grating as a standard dispersion-piece for investigative work in sensitometry*, when used without the addition of a prism.

Inasmuch as anything is a "standard" if we know what it is, we may begin first with the material of which the replica-grating is manufactured. We have a definite compound, collodion, resulting from the mixture of amyl acetate and pyroxylin, which is always prepared in the same way. The replicas themselves are composed of the same amount of solution, dried under similar conditions, and give a film of the same thickness. These replicas are made from the same original, and are therefore practically identical, while the grating from which they are made gives a fairly even distribution of light throughout the various orders. These films are mounted upon glass of similar thickness, quality, absorption, and refractive index.

There is no possibility of surface oxidation of the replica, nor does selective absorption enter into the account¹ for all the methods necessary to a complete test of photographic plates.

Inasmuch as the distribution of intensity is greatly dependent upon the shape of the groove made by the cutting diamond, it may be argued that equally minute differences in the grooves of the replica-grating would have the same effect. While this is undoubtedly true, yet, as a matter of fact, such differences, although looked for, have not yet been detected. In a spectro-photometric examination of a number of replicas, all made from the same original, at different times throughout the course of five years, which had been prepared under temperatures varying about 8° C., the results were gratifyingly exact. The method of manufacture, however, would indicate such results, when we consider that the shrinkage in the drying would be

¹ *Astrophysical Journal*, 22, 129, 1905.

identical, provided the conditions and materials were similar. Obviously the same argument applies to the method of mounting.

While it is not claimed that the replica-grating is perfectly suited for all classes of work, yet it is believed that its adoption in sensitometry would avoid the great lack of accord between the results of one worker in photography and that of another, with the unprofitable discussion which inevitably ensues.

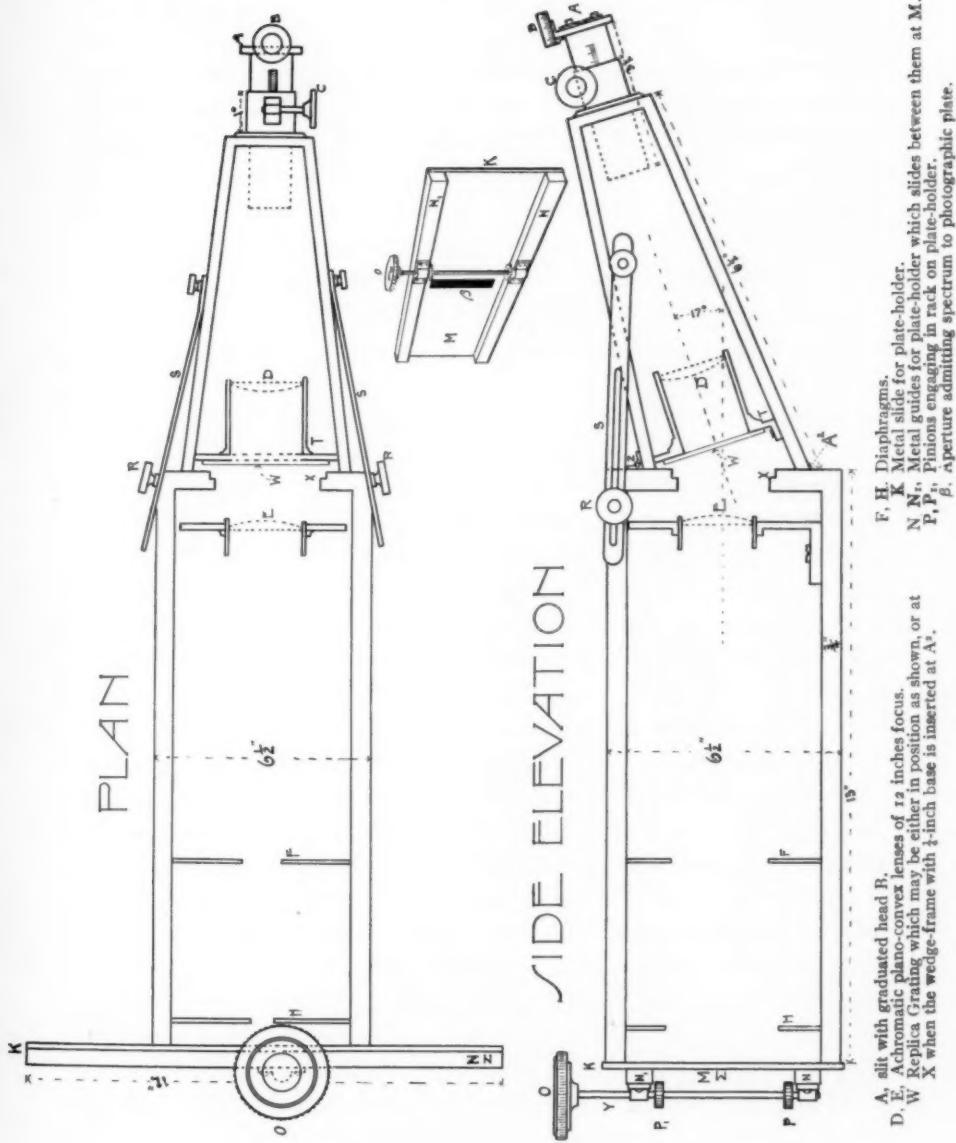
After many experiments, and consultation with authoritative scientists, the writer offers this form of grating to the photographic investigator for adoption as a standard dispersion-piece in sensitometry, in the hope of establishing uniformity in photographic results. In order, furthermore, that this standard may be disseminated widely and be of universal application, the writer has decided to present to each known investigator in photography of any nationality, who may apply, one of these standard replicas of a size suited to his needs.

It may be argued that no replica-grating can be compared in defining power with an original ruling. Argument upon this point is unnecessary, inasmuch as what is wanted for photographic investigation is not critical definition of spectral *lines*, but the correct definition of spectral *hues*. In most of the negatives the Fraunhofer lines are purposely obliterated, because they interfere with the measurement. It is, however, now a matter of common knowledge that good-quality replica-gratings leave little, if anything, to be desired on the score of definition, and, except for the spectroscopy of position, even those of secondary quality define *far in excess* of the requirements of the work in hand.

REPLICA GRATING SPECTROGRAPH

The form of spectrograph suggested for use with the replica has been modeled along lines somewhat similar to an instrument devised by Baker,¹ but possesses several modifications. Its plan may be easily understood by reference to the drawing (Fig. 4). Simplicity combined with rigidity was the principal aim in the construction of the instrument. Lenses of greater focal length could be used for the formation of a longer spectrum without any difference ensuing save

¹ *Journal Royal Photographic Society*, 46, 161, 1906.



in the length of exposure time, but the dimensions of the instrument would thereby be increased. With the specifications given the spectrum measures 6.2 cm from λ 6900 to λ 3550 (B-N), which is of good measurable length. For special examination of the red and infra-red end a narrow brass wedge-frame is inserted at A^2 , which changes the angle of the collimator and brings the C line (λ 6563) in the center of the plate. To enter here into a discussion of the resolving power of the instrument is unnecessary when we take into consideration the work for which it is intended. The spectrograph may, if furnished with slit and lenses of good quality, be used for a very high grade of spectroscopic work. For visual observation an eyepiece can be held by means of an adapter at the plane of the plate.

The spectrograph should occupy a definite permanent position in the laboratory, with the collimator pointing to the northern sky always at the same angle. This latter point is provided for in the construction of the instrument. The width of the slit should remain constant, and all the light reaching it should pass through thin milk glass or other diffusing medium, free from selective absorption. Exposures for the determination of selective sensitiveness should not be made unless the altitude of the sun is greater than 15° . The length of exposure which constitutes the beginning of the series varies with the speed of the plate—i. e., longer with a “slow” than with a “fast” plate. In the case of the Seed “27” plate (as indicative of fast plates) the exposures found most suitable run as follows: 2, 5, 15, 30, 60 seconds, 2, 4, 8 minutes; these eight exposures, together with two others yet to be described, occupying the entire $3\frac{1}{4} \times 4\frac{1}{4}$ plate. With a “slow” plate the first two exposures are omitted. Obviously it would not be advisable to adhere closely to those times when using sky light under *extreme* meteorological conditions such as exceptionally bright on one day and raining on the next.

PHOTOMETER

It may be proper at this place to consider the instrument constructed for the measurement of photographic densities.

A very complete bibliography and discussion relative to photometers suited to this class of work are given by Mees and Sheppard

in their paper "Sensitometric Investigations."¹ Following this, the writer had constructed a Hünfer spectrophotometer; but, after experimenting some considerable time with this form of instrument, it was discarded in favor of a modified Brace prism instrument, as the permanent line dividing the two fields under comparison was found very objectionable, and prevented a match of as high a degree of accuracy as if the shades actually adjoined one another.

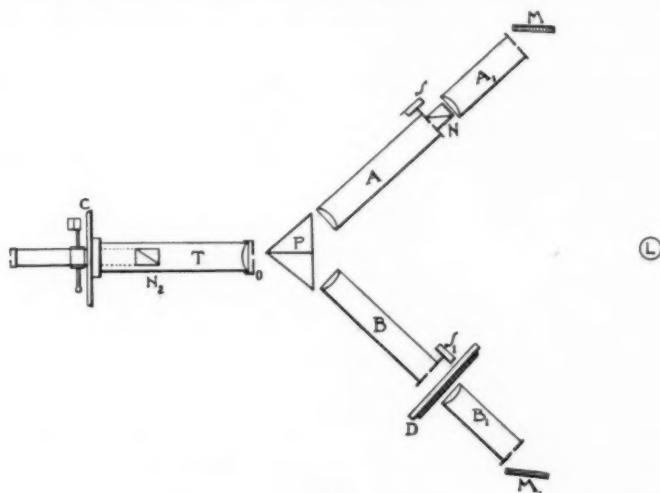


FIG. 5

In Brace's original instrument² measurement of differing intensities is made by varying the slit-width on one of the collimators, the readings taken being in terms of the screw-pitch (or slit-width), the optical value of which may be obtained by interpolation upon a scale derived from a previous calibration by means of a rotating sector-disk. In order to make the instrument more particularly suitable for the measurement of photographic plates, a number of changes and additions were made, which will now be described.

Immediately in front of, and in contact with, one of the collimator slits *A* (Fig. 5), a Nicol prism *N*, was mounted; while in front of that, and in line with its axis, a supplementary collimator *A*₁ is carried by a

¹ *Journal Royal Photographic Society*, 44, 200, 1904.

² D. B. Brace, "On a New System for Spectral Photometric Work," *Astrophysical Journal*, 11, 6, 1900.

rigid supporting-piece. Collimator *B* was also furnished with a supplementary collimator *B*₁, the function of each being the delivery of a beam of parallel light to their respective slits *S S*₁.

An analyzing Nicol *N*₂ is carried in the telescope tube *T* (which has been lengthened in order that the rectangular diaphragm in front of the objective *O* might be in distinct focus). The angle of rotation of the analyzer is read upon the graduated circle *C*. Beyond each of the two collimators *A A*₁ two mirrors *M M*₁ are fed from 150 c. p. incandescent lamp at *L*.

The plate whose opacity is to be measured is held in a special carrier *D* between collimators *B B*₁, where, by means of a sliding-piece, the differing opacities are brought successively into position in front of the bilateral slit.

The dispersion-piece employed is the now well-known Brace prism *P*, which is made up of two equal 30° flint prisms of refractive index 1.64822 for D, and carries on one of its inner surfaces a deposited silver strip 5 mm in width, the two prisms being cemented together.¹ When first constructed, this cementing medium was alpha-bromo-naphthalin, which possesses a refractive index very close to that of the glass used. Constant trouble was, however, experienced on account of the volatile nature of this medium and the difficulty of sealing it in and eventually the prism was taken apart and recemented with Canada balsam. On account of the difference between the refractive index of the balsam and that of the glass, there is always present a small amount of reflected light; but as this light is proportional to the intensity of the incident light, it introduces no error in the readings worthy of any consideration, and is visible only when measuring very low densities.²

In adjusting the instrument for use, the prism table is raised until the beam from collimator *B* passes slightly below the center of the prism, and the field presented when viewed through the observation tube *T* (which carries no eye-lens, being pierced only with a 2.5 mm

¹ This prism was ground and polished by Mr. O. L. Petitdidier, of Chicago, to whom thanks are due for its optical excellence.

² Experiments are at present under way toward the adjustment of a balsam or non-volatile cementing medium of similar refractive index to the glass employed in the prism.

circular opening) is an illuminated rectangle, which is of even brightness throughout (*A*, Fig. 6), when all adjustments are made, and the light is equally intense from either collimator. Should one beam be possessed of greater intensity, the field will show two squares of differing brightness (*B*, Fig. 6). This arrangement has been found more satisfactory in practice than that usually

employed, viz., when the light enters the prism centrally and the field is shown crossed by the image of the silver strip, as in *C*, Fig. 6.¹

When beginning a series of measures upon photographic plates, the slits on their respective collimators are first opened to approximately the same width, the greatest opacity in the plate to be measured is run into position, and a rough trial match is made, the object simply being the assurance of sufficient slit-width to give light enough for the lowest measure without running too close to the extinction point (zero). In practice it is not deemed advisable to read an opacity requiring a smaller mean angular measure than 2° (=approximately 3.0 units of Hurter and Driffield).

The mirrors are carefully adjusted to reflect their light centrally through each collimator. Then, while the eye observes the interface of the prism through the telescope tube, and with the analyzer set at 90° , slit *S* is altered slightly in width until an exact match is obtained between the two halves of the field, which is indicated by the *absolute disappearance of the dividing line*. From now on until the measurement of the plate is completed, neither slits, light, nor mirrors should be moved or altered.

The varying opacities are now slid successively into position in front of slit *S*, and the analyzer rotated until a match with each is secured. As the zero of the analyzer circle indicates the point of extinction, the formula for the expression of the luminous intensity is $\sin^2 \theta$, where θ = the angle of the analyzer, while the degree of



FIG. 6

¹ It would probably serve the purpose better if the silver strip covered the entire lower (or upper) half of the interface. The beam of parallel light from the collimators could then pass centrally through the prism, and the single dividing line would fall in the center of the field of view.

blackening when represented in Hurter and Driffield density units $= \Delta \log \sin^2$ from the "fog value."¹ In practice, readings made from both sides of the extinction point furnish a mean which eliminates any error due to the false position of the zero.

The method of recording the measures obtained is shown in Table I, which presents the density measurements of Plate 2 "lower" (see page 137).

TABLE I

No.	ANGLE		MEAN	LOG SIN ²	$\Delta \log \sin^2$ (= DENSITY)
	Above	Below			
Fog.....	76.5	72.8	74.8	9.9691	
1.....	66.0	67.5	66.8	9.9268	.0423
2.....	55.9	54.5	55.3	9.8299	.1392
3.....	42.0	43.5	42.8	9.6644	.3047
4.....	32.5	35.1	33.8	9.4906	.4785
5.....	25.1	28.0	26.6	9.3220	.6671
6.....	20.6	23.0	21.8	9.1306	.8295
7.....	15.5	18.5	17.0	8.9318	1.0373
8.....	12.7	15.6	14.2	8.7794	1.1897
9.....	9.9	12.8	11.4	8.5918	1.3773

As an example of the agreement in the measures of different observers a large number of settings were made by Messrs. Parkhurst and Jordan and the writer, upon the same opacities, A, B, the results of which are given in Table II.

TABLE II

OBSERVER	MEAN ANGULAR MEASURES		LOG SIN ² θ (= DENSITY)	
	A	B	A	B
J.....	14°05	9°205	8.7674	8.4076
P.....	13.93	9.250	8.7642	8.4122
W.....	14.05	9.220	8.7674	8.4090

(Mean of 12 settings for each value)

Probable error of average $\pm .0009$

Difference: Density A = .0032

Density B = .0046

It is well known that in visual photometry the position of the star relative to the comparison light exercises an influence upon the measures, and for this reason it was deemed advisable to test the

¹ A table was constructed giving the value of $\log \sin^2$ from 0° to 90° in tenths of a degree, thus enabling rapid work.

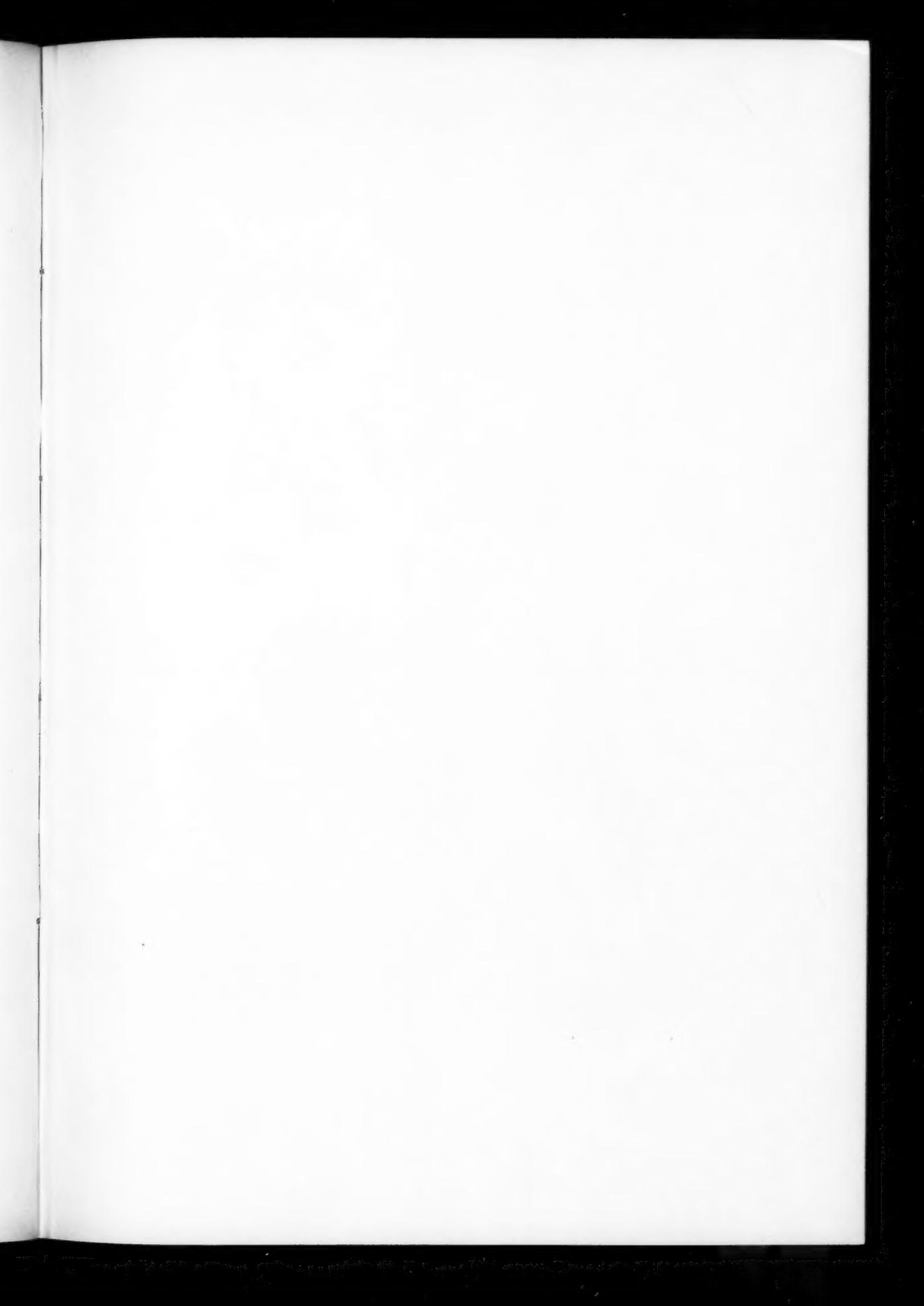
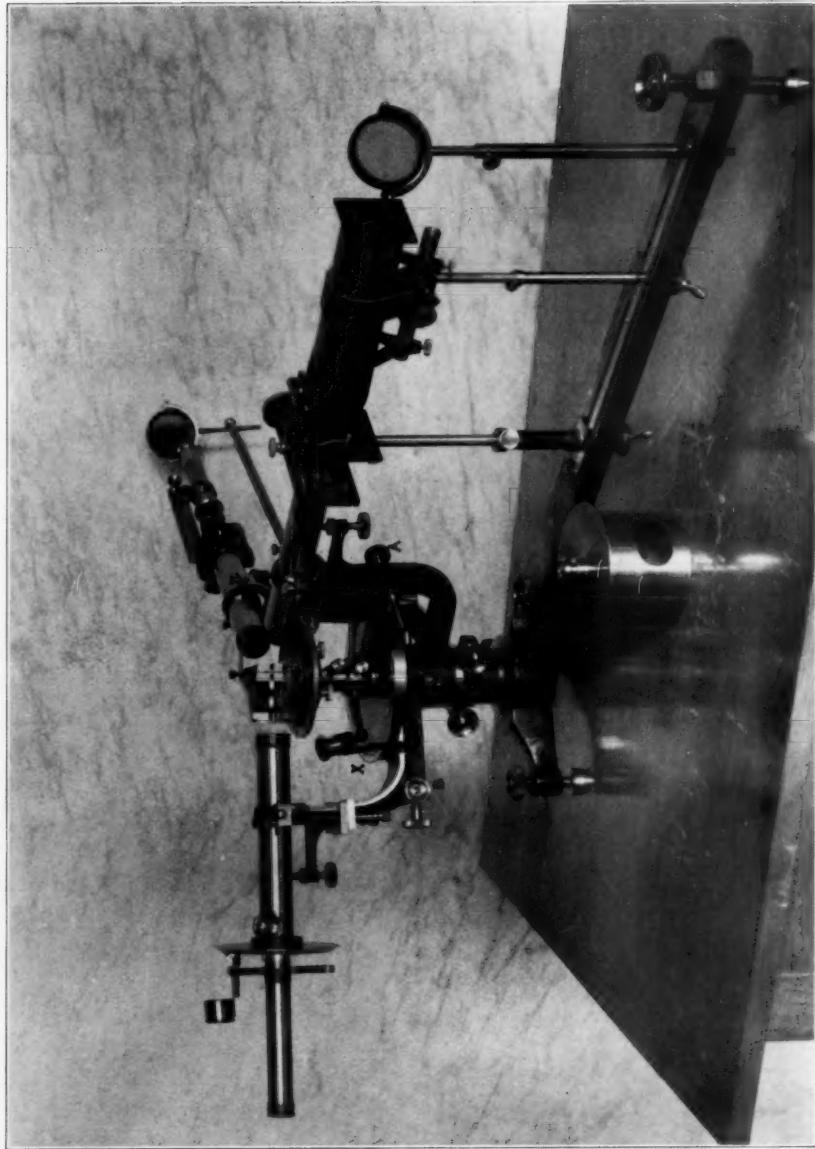


PLATE IX



SPECTROPHOTOMETER FOR MEASUREMENT OF PHOTOGRAPHIC OPACITIES.
($\frac{1}{8}$ NATURAL SIZE).

match obtained in the spectro-photometer with reference to the vertical and horizontal positions. As it was not practical to arrange the instrument to show the two squares in a horizontal plane, all measures were made by alteration in the position of the observer. Professor Barnard and Mr. Parkhurst kindly made the necessary settings, and from a mean of ten in each position, for each observer, the net result obtained was not above the error of observation. The instrument may therefore be regarded as free from error in this regard.

In using the instrument as a spectrometer, special fronts have been constructed for holding color-cells, etc., while the records are made from readings on the divided circle *X*, which is carefully graduated on silver, and reads with two verniers direct to $20''$. The prism-table is also graduated. Collimators *A* and *B*, together with the observing telescope *T*, rotate around the optical center of the instrument and are furnished with clamping screws. *T* and *B* are also equipped with tangent slow-motion screws for delicate adjustments. It is, however, not advisable to disarrange the instrument when set up and adjusted for photometry, but to make use instead of separate instruments for different lines of work. The aperture is 25 mm. with a focal length of 200 mm. Plate IX is made from a photograph of the completed instrument.¹

Another important point regarding this instrument is the ability to displace the two spectra horizontally relative to each other, so that the red of one spectrum is in juxtaposition with any hue in the other by movement of the single slow-motion screw shown at *A*, Plate IX, while direct measurement may be made in any region of the matched spectra by movement of the slow-motion screw *B*.

The spectrophotometer as just described was constructed for various lines of work requiring critical measurement, but such an instrument is by no means essential. The extremely simple and ingenious arrangement devised by Pfund² should be well able to meet all of the requirements in ordinary density measures.

¹ Originally the photometer was a three-arm spectroscope constructed by Gaertner, of Chicago, with his usual skill. The alterations necessary to convert it into its present form were made by the writer in the instrument shop of the observatory.

² *Johns Hopkins University Circular*, 4, 20, 1906.

INFLUENCE OF LIGHT IN SENSITOMETRY

The next point in order of importance is the nature of the light used for the determination of selective spectral sensitiveness, and upon this point there seems to be as great a diversity in modern usage as there is in the spectroscope employed. It is conceded on every hand that daylight is the illuminant *par excellence*, but the impossibility of obtaining such light, constant in intensity and quality, has led to the substitution of almost every known source of illumination.

If the question were one which concerned only the integrated luminosity, the difficulties could be much more readily overcome. But unfortunately the distribution of spectral intensity is a more potent factor. One has but to compare the spectra of the various sources, even roughly, to find that they present no agreement among themselves. Some are deficient in the red rays, while others are deficient in the violet (Plate VIII).

In the comparison of the acetylene flame (*a*), the spectroscope was arranged with a Hünfer-Albrecht rhomb immediately in front of and in contact with the slit-jaws. One of the rhomb surfaces was illuminated by a beam of diffused daylight, while the remaining incident surface received a beam from the diaphragmed acetylene flame. The distance of the burner from the slit was altered until the spectra appeared visually equal in the green. Exposures were then made upon a Cramer isochromatic plate for varying lengths of time, the daylight and acetylene spectra impressing themselves simultaneously.

In the comparison of the candle (*b*), benzine (*c*), and *Mg* (*d*) flames, and the incandescent electric light (*e*), the replica-grating spectrograph was used without the rhomb, daylight exposures being made at the beginning and end of each series.

The great lack of ultra-violet in *a*, even with extreme overexposure, is readily observed, together with the strong action of the yellow-green, which with a suitable plate would be shown as extending with increasing action into the red. In *d* this effect is reversed, and the maximum action is shown to lie in the ultra-violet (as is also the case in the use of the electric arc-light); *b* and *c* are very similar to each other, and show the characteristic drop in the ultra-violet, with the corresponding increase at the red end.

PLATE VIII

Diffracted (Fig. 1) and Prismatic (Fig. 1a) Daylight Spectrum on Cramer Trichromatic Plate

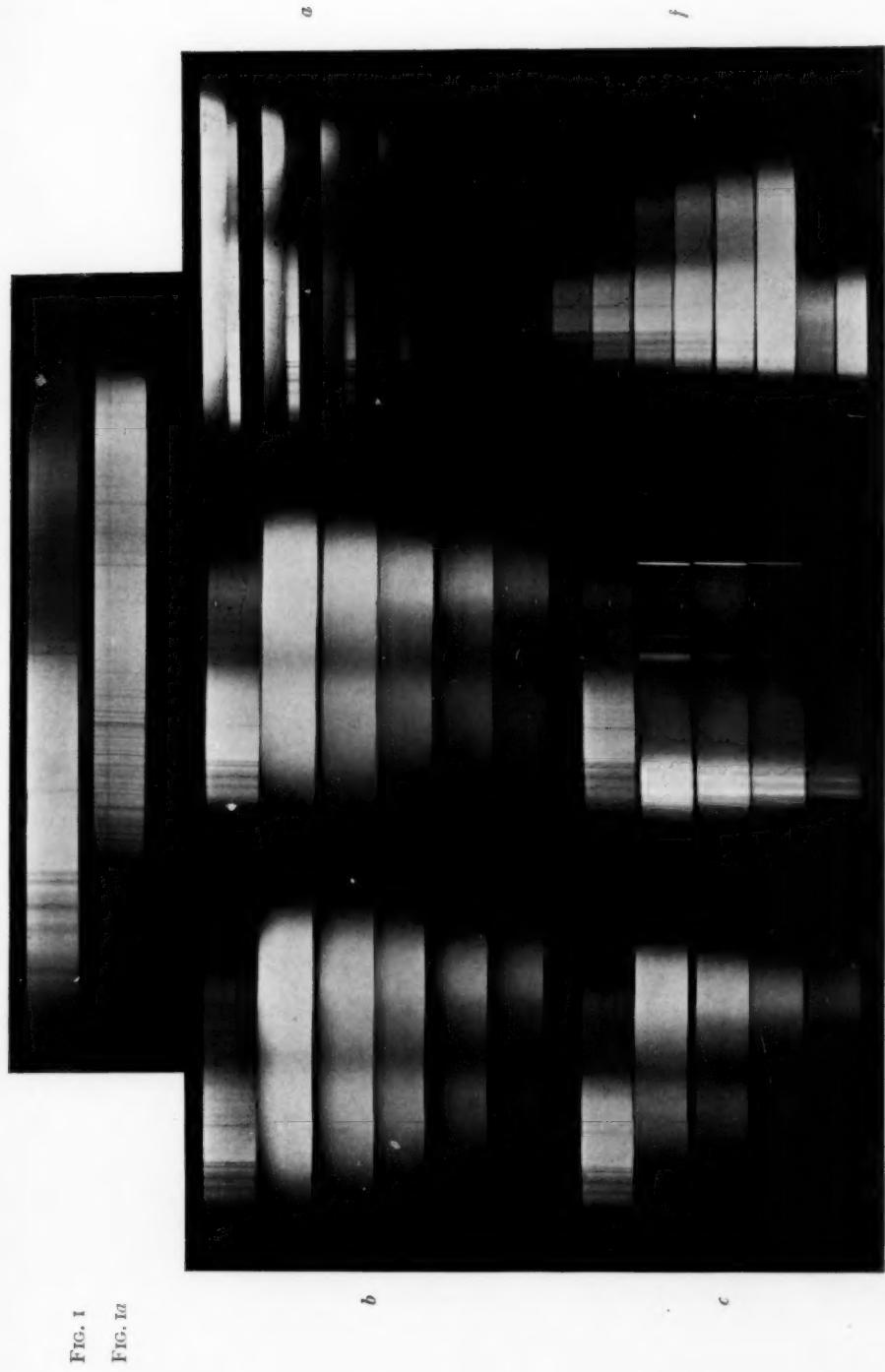


FIG. 1

FIG. 1a

COMPARISON OF LIGHT-SOURCES USED IN SENSITOMETRY

b, Candle Flame; e, Incandescent Electric Light.
c, Scheiner Benzine Flame. d, Magnesium Flame.
f, Cramer "Inst. Iso." plate.



Notwithstanding that this is a point to which many workers have directed attention, yet unfortunately in the majority of cases those same workers continue their use and publish spectral comparisons of plates made with the same light-source which they condemn, and for which they give no correction factor. It is obvious that the relative selective sensitiveness of two plates determined by a light vastly different from daylight cannot furnish any reliable quantitative information regarding the true values of the plates, unless the artificial light be accurately calibrated in terms of daylight (by photographic means), and a formula derived from such calibration which may be used as a correction factor.

Efforts have been made to calibrate a light to the spectral value of daylight, and though several approximations have been arrived at, yet we are still far from a satisfactory conclusion. The latest and best work in this direction is due to Mees and Sheppard,¹ who have suggested as a standard, acetylene gas, burning under constant pressure, and with special care as to its purification, etc., to insure constancy in the luminous intensity. This latter point presents no especial difficulty. Inasmuch as the flame of acetylene gas is greatly deficient in the violet end of the spectrum, they devised a compensating color-filter to correct this deficiency, whose action may be briefly explained by stating that it was intended to absorb proportionately the excess from the least refrangible end of the spectrum. While this combination was undoubtedly an improvement, yet it was by no means satisfactory, and that this was recognized by these careful investigators themselves is proved by the introduction of still another make of filter in a later publication.² This latter filter can, however, still be considered as no more than an approximation, which is indeed what these workers themselves term it.³

There are, however, numerous opportunities for the use of a standard artificial light, in which the difference in spectral distribution from daylight does not enter greatly into consideration, and for such the acetylene "standard" of Mees and Sheppard offers decided

¹ *Journal Royal Photographic Society*, **44**, 293, Nov. 1904.

² *Ibid.*, **46**, 114, 1906.

³ *British Journal of Photography*, **53**, 797, 1906.

advantages. The writer has made use of a somewhat similar arrangement with most satisfactory and encouraging results.

The question now is: Does an approximation so arrived at offer any advantages over diffused daylight, if used under certain conditions, when applied to the determination of selective sensitiveness? Briefly, I hope to show that it does not.

DAYLIGHT (VARIATION IN COLOR)

It has been many times stated that daylight was utterly unsuited for sensitometric tests, because of (1) the difference in the intensity of the various hues as the slit is illuminated by white cloud or blue sky, and (2) the variation in general brightness-intensity. Experiments were made to determine the actual difference in the first instance, by using the replica-grating spectrograph as just specified. The instrument was so arranged that the axial line of the collimator pointed directly to the zenith. Immediately over it was held a Zeiss apochromatic lens of 314 mm (12.4 in.) focal length, which formed an image of the cloud upon the slit-plate. Several exposures were made on different dates, and on various makes of plates, only such days being chosen as presented well-defined cumulus clouds in a clear and intensely blue sky. Care was taken that the slit was entirely filled with the cloud-light or blue sky, as the occasion demanded and exposures were made to immediately follow one another, the exposure times being from 5 seconds to 1½ minutes, and on the same plate.

The results were exceedingly interesting, the negatives from the blue sky showing, as was to be expected, an absorption of the complementary hues at the least refrangible end. This absorption was, however, but slight in general. Those negatives whose timing showed the greatest contrast-difference were selected for measurement, together with a plate exposed to the spectrum from the same sky, but with the lens removed and a sheet of ground glass interposed in its place.

Density measurement of these negatives gives the results as detailed in Table III.

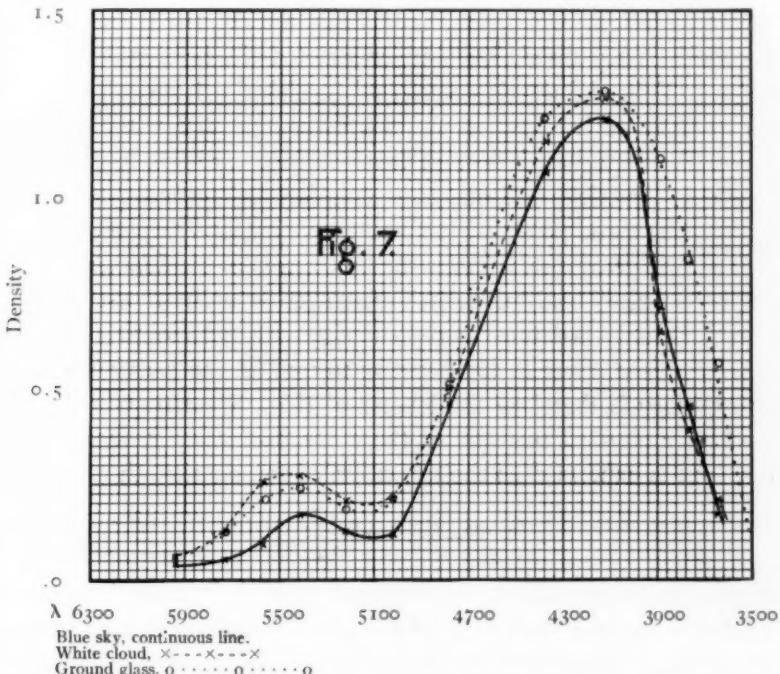
When plotted, these results give the curves of Fig. 7.

It will be noted that the difference between the secondary maxima in the yellow-green, when expressed in density, =0.11, and this amount would be still further reduced if the "blue sky" negative had

TABLE III

WAVE-LENGTH	DENSITY		
	(Blue Sky)	(White Cloud)	(Ground Glass)
3640.....	0.1750	0.2122	0.5731
3760.....	.4536	.3956	.8401
3880.....	.7106	.6498	1.1121
4120.....	1.2124	1.2638	1.2861
4370.....	1.0702	1.1486	1.2182
4780.....	0.4592	0.4992	0.5112
5020.....	.1172	.2234	.2194
5220.....	.1218	.2012	.1896
5410.....	.1636	.2739	.2400
5570.....	.0952	.2619	.2109
5730.....	.0494	.1201	.1253
5940.....	.0382	.0676	.0666

been exposed for a slightly greater length of time. The strong absorption in the ultra-violet from $\lambda 3400$ to $\lambda 3700$ in the "cloud" and



"sky" negatives is, of course, due to reflection and absorption by the component parts of the lens-system. On the other hand, a

change in altitude of the observer would show a still greater difference, the "blue" of the sky becoming more intense as the altitude increased, and necessitating an increase in the exposure time.

Comparison of these results, together with comparison of exposures made when the collimator formed an angle of 25° with the plane of the horizon (which of course showed considerably less difference), indicates that daylight from a low angle, when properly diffused, is a sufficiently reliable guide for practical tests in selective sensitiveness. The second objection will be dealt with presently.

HURTER AND DRIFFIELD'S INVESTIGATIONS

To correctly understand and appreciate the argument advanced for the use of daylight as a standard in plate-testing necessitates a fairly clear understanding of the work of Hurter and Driffeld, whose "Photo-chemical Investigations"¹ first raised photography from mere rule-of-thumb practice, and placed it upon a definite basis of scientific fact. They discovered and enunciated the laws governing the action of light and development, and furnished a terminology which is not likely to be supplanted. Unfortunately, for some unknown reason the important results of these eminent workers are but little known in America, and one may therefore be pardoned for briefly capitulating those points which bear directly upon the present paper.

The first great distinction made by them is in the definition of the terms "opacity" and "density," which are in ordinary use, synonymous. *Opacity* is defined as representing merely the optical property of the reduced silver in the negative to impede the passage of light; *transparency* is therefore the inverse of this. *Density*, on the other hand, is a physical measure of the amount of silver reduced in the film, and is expressed as the logarithm of the opacity, thus

$$D = \log O = \log \frac{I_1}{I},$$

where I = the intensity of the light transmitted, I_1 = the intensity of the incident light, and O = the opacity. This distinction between opacity and density must be firmly fixed in the mind.

If a plate be impressed with a series of different accurate exposures

¹ *Jour. Soc. of Chem. Industry*, May 31, 1890.

increasing in geometrical progression, as 1, 2, 4, 8 . . . 256, and developed, and the resulting scale of opacities be measured, it will be found, that if the logarithms of these opacities are plotted (densities), there will result a characteristic curve. The central portion of this is practically a straight line, and throughout this straight portion the deposits of reduced silver (blackening) will increase in arithmetical progression, as 1, 2, 3, 4, . . . 9; that is, there is a definite logarithmic relationship between the amount of light acting and the action itself. The density unit is the density of a deposit which transmits the tenth part of the incident light.

The enunciation of the law of "constant density ratios" provoked considerable controversy from photographic workers in general; but, while the investigators' conclusions were disputed, they advanced to the support of their statements definite scientific proofs which confirmed them. It was found that the relation existing between the amount of light and the density-ratios is fixed and unalterable by the constitution of the developer, or time of development; the *opacity* ratios are, however, altered. For example, suppose that a plate exposed to light for a definite length of time behind a revolving sector-disk with graduated apertures be cut into two portions, and each portion be then developed for a different length of time, we should obtain as a result negatives which differed greatly in their appearance one from another; that is, that one which had received the shortest time of development would be what is termed a "thin" negative, while that receiving the longest time of development would be what is usually termed "contrasty." Yet the ratio existing between the densities would be identical, although the opacity-ratio varied, the increase in development causing the various densities to grow, but in such a manner that they would still bear the same ratio to one another. When the opacity-ratio is the same as the ratio of exposure, the negative is the true inverse of the original. The determination of the characteristic curve shows that a plate has considerable "latitude" in exposure,¹ so that negatives developed together which had received greatly different exposures would yield identical prints, provided that the exposures lie within the straight portion of the curve.

¹ "Latitude" is defined as the ratio of the exposure at which over-exposure commences to that at which underexposure commences.

On the other hand, in the case of two negatives developed for a precisely similar length of time, but with one exposure double that of the other, we have the opacity-ratios constant, while the densities vary. In other words, the extra exposure simply means the addition of an equal amount of deposit on the varying densities composing the negative, and merely affects the time required in printing. To such an extent is it possible to vary the exposure time (with constant development) that increasing exposures of from *one to sixteen times* normal will produce identical prints, the only real difference between them being the time occupied in printing. The negatives, however, *appear* vastly different from one another. This fact was exceedingly well illustrated recently in a photographic magazine.¹

VARIATION OF MEAN INTENSITY IN DAYLIGHT

With this explanation we may now consider the second objection to the use of daylight, namely, the variation in the mean intensity. It will readily be perceived that this intensity-variation of course amounts to nothing more than an alteration in the length of exposure, and therefore comes under the jurisdiction of the law expressed in the preceding paragraph. In order, not only to test the validity of the law, but also to obtain a personal measurement of the photographic light-change during the course of a few hours, the following exposures were made with the revolving sector-disk,² under conditions as specified. The record detailed in Table IV is from the laboratory notebook.

All four plates were developed together in the same tray with rodinal 1 : 24, for two minutes, at a temperature of 17° C., and, when fixed and dried, were carefully measured, and the densities plotted. The resulting curves are shown in Fig. 8, and it will be readily seen that they bear out very exactly the theoretical requirement that they lie parallel to one another. Their density-ratios vary, but their

¹ F. Dundas Todd, "Development, Scientific and Practical," *Photo-Beacon*, 16, 300, 1904.

² The sector-disk exposure machine was constructed somewhat similar to the arrangement of Mees and Sheppard (*Journal Royal Photographic Society*, July 1, 1904, p. 229), but fitted with a removable cap pierced with a 4.0 mm circular aperture and covered with ground glass for use with daylight. When working with the constant acetylene light, the cap is removed and the burner instantly placed in position.

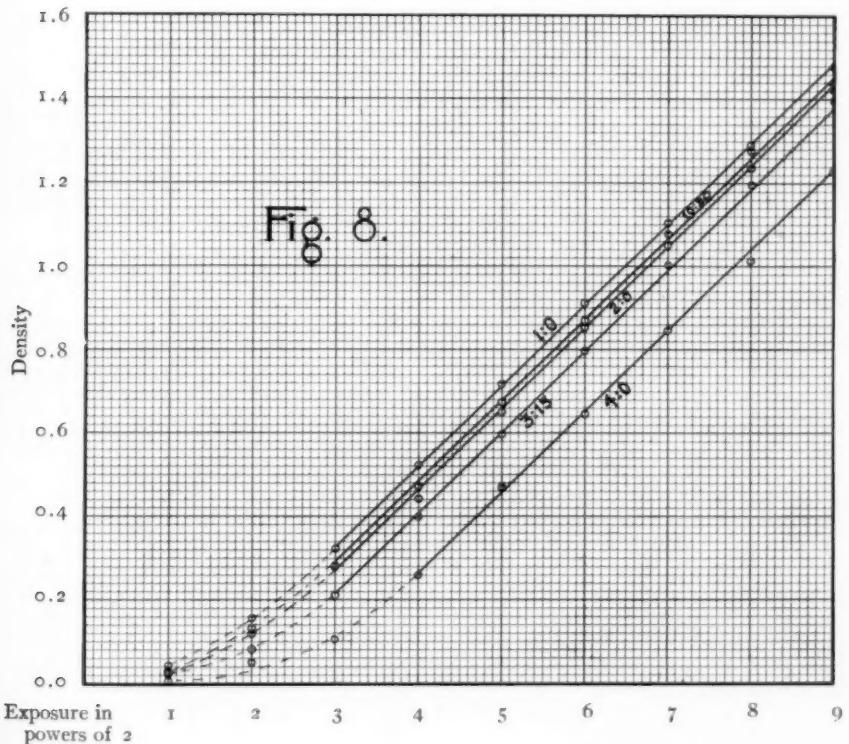
TABLE IV

Sky bright and sunny. Plate, Seed "27" Emul. 11168; Oct. 12, 1906

Plate No.	Time of Exposure	Position on Plate	Length of Exposure	Remarks
1.....	10 A.M.	Upper half	3 min.	Blue with white clouds
1.....	10:30 A.M.	Lower half	"	Blue with white clouds
2.....	11:15 A.M.	Upper half	"	Slightly brighter
2.....	12 M.	Lower half	"	Slightly brighter
3.....	1 P. M.	Upper half	"	Still brighter
3.....	2 P. M.	Lower half	"	Intensity about the same
4.....	3:15 P. M.	Upper half	"	Slightly duller
4.....	4 P. M.	Lower half	"	Light much weaker

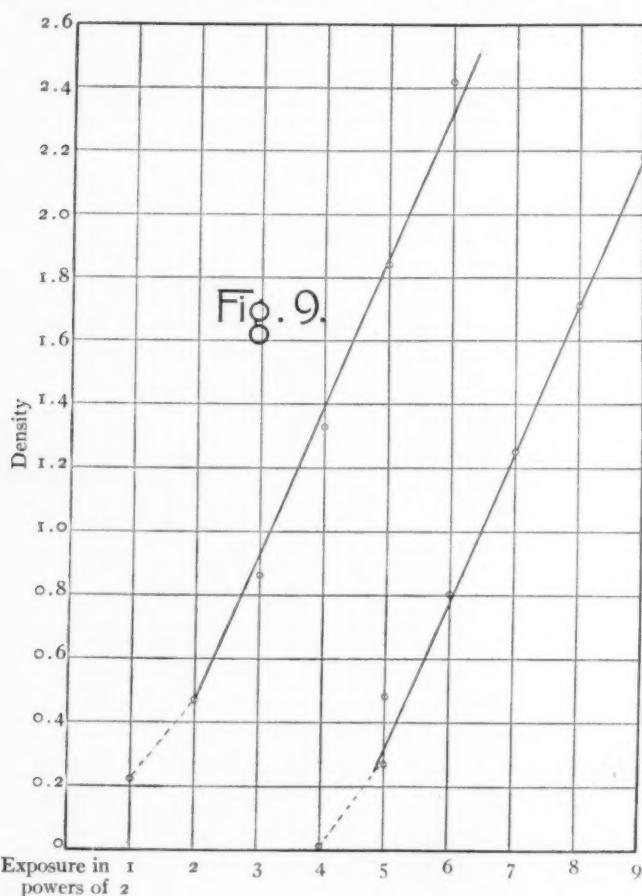
Two exposures on each plate. All four plates cut from one large plate.

opacity-ratios are constant. Between 1 P. M. and 4 P. M. there is an indicated difference in light-action of $2^{1.3} = 2.5$ times, which allows for considerable fluctuation in light-value. But that this is by no



means a limiting value is shown by the parallelism of the curves in Fig. 9, which represent a difference in light-action of $2^{3.3}$ or 9.8 times. There is no difficulty in obtaining any amount of corroborative data in this connection.

It should be remembered, that with varied exposure and equal time of development, we obtain, as the exposure is increased, an addition



of an equal density (or fog) to the complete negative; but this increase of density does not in any way alter the opacity-ratios existing between the series of exposures on the same plate (throughout the straight portion of the curve), such opacity being governed by the development:

there is no alteration in the gradation. Hence the curves of two differently exposed spectra would, as a whole, be parallel to each other, although the height of the ordinates (densities) would vary.

IRRATIONALITY OF PLATE CURVES

To be able to refer to the speed of any particular plate as possessing a definite numerical value presents advantages which cannot be disputed. But if such a numerical value is based upon some source of selective radiation which differs from daylight, such as a candle in the case of Hurter and Driffield, the screened acetylene light of Mees and Sheppard, or the benzine lamp of Eder,¹ then the comparative speed-values obtained for "ordinary" and orthochromatic plates, are *certain* to be unreliable to a greater or less extent, dependent upon the closeness of the approximation of the artificial standard to daylight, and they must therefore be accepted provisionally.

A method commonly in use in testing the speed of one plate against another, is to expose the two plates to identical amounts of the same light-action, and then develop them together in the same tray for a similar length of time, and compare the resulting negatives. Provided that both plates have a similar composition, the method cannot be objected to; but when the plates in question are possessed of a different chemical constitution (the consideration of orthochromatic plates being laid aside for the moment), such a method is very liable to lead in many cases to most erroneous conclusions.

If two pairs of differently constituted plates (A, A_1 , and B, B_1) be exposed simultaneously to the same light-action, and then developed together, giving one pair double the length of time of the other, as $AB = 3$ minutes, and $A_1B_1 = 6$ minutes, it is very common to find, that with the first pair where A possesses a greater density than B , in the case of the second pair with the lengthened development, the effect would be entirely reversed and B_1 will have a greater density than A_1 . The following series of plates was therefore prepared: a Seed "27" and a Cramer "instantaneous isochromatic" were exposed to precisely the same amount of light-action behind the revolving sector-disk, and then cut into eight strips each in the

¹ Eder and Valenta, *Beiträge zur Photochemie* (French translation by Belin, entitled *Système de sensitométrie*).

dark-room. All of these strips began development together in the same bath at the same time, but, at stated intervals, each pair of plates ("27" and "Iso.") was removed from the developer together and

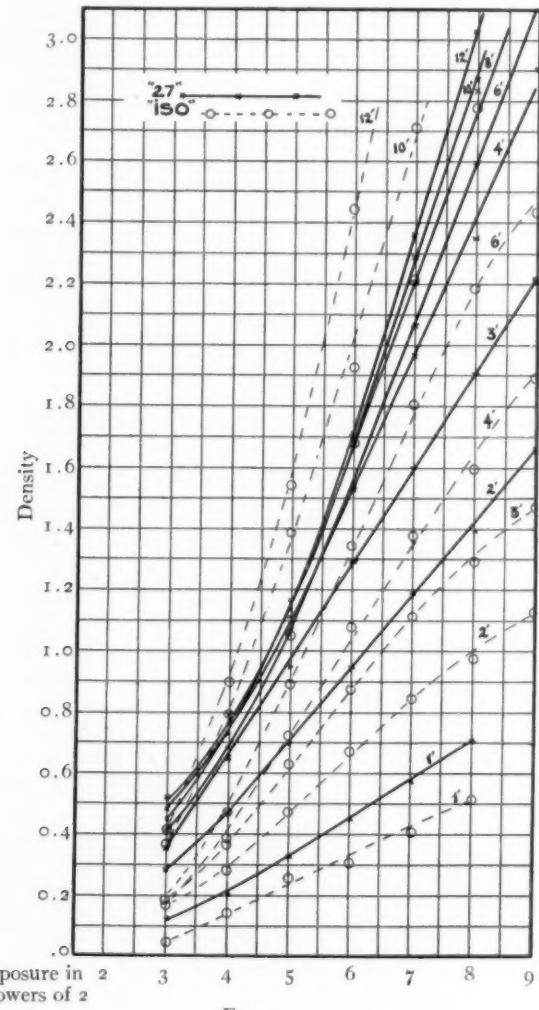


FIG. 10

passed directly into the fixing bath. From the measurement of these negatives the curves shown in Fig. 10 were plotted, and serve well to illustrate this phase of plate-action.

It will be noted that, with but one exception (8 minutes), no single pair of plates gives curves which are parallel to themselves. The gradation of the two plates is entirely different. In the present instance the Cramer plate is known to be slightly slower than the Seed, and hence it will be perfectly correct for the curve of the former to lie lower than that of the latter; but it will be seen that, if we measure the distance apart of these curves representing the various development times, it is a constantly decreasing quantity up to a certain point, namely, that at which the slope of the straight portion of the curves are similar; and from that point on, the conditions are absolutely reversed, and the isochromatic plate acquires a greater density than the "27," and appears the faster plate of the two. Under the method of equal time of development, therefore, no true deduction could be made regarding the relative speed of these plates from any of the eight pairs of curves shown.

It has been shown by Abney¹ that a change in the gradation-curve takes place when the exposure is to light of differing wave-length, the curve becoming steeper; that is, the contrasts are more marked as the wave-length increases. In the present instance with normal development the curve of the "Iso" plate is less steep than its accompanying "27" plate, although it is sensitive farther toward the less refrangible end of the spectrum. It would appear, therefore, that the change in the slope of the curve is due mainly to the constitutional (chemical) difference between the two plates, which leads to a difference in the velocity of the chemical reaction in ordinary development.

In order, then, to obtain a direct comparison between two plates, it is necessary *not* to develop for precisely similar lengths of *time*, but for precisely *similar amounts of development-action*—i. e., reduction product; under which circumstance the gradation-curves will lie parallel to one another. In trichromatic work, where different plates are used and the development is for equal times, as is very commonly the case, this change in the gradation-curve due to constitutional plate-difference must therefore be as carefully guarded against as is the change in gradation due to difference in wave-length, if the true color-value of the object be seriously considered.

¹ "On the Variation in Gradation of a Developed Photographic Image," *Proc. R. S.*, **68**, 300, 1901.

DEVELOPMENT FACTOR

In the development of either the spectral records or the sector-disk exposures it will be evident, therefore, that the duration of development is of considerable importance. Hurter and Driffield have named the amount of development received by a plate the "development factor" (γ). This factor may be calculated from their formula

$$\gamma = \frac{D_2 - D_1}{\log E_2 - \log E_1},$$

where D_1 and D_2 are two densities selected from the straight portion of the curve, lying as far apart as possible, and $E_1 E_2$ = the relative exposure times for the densities considered. It was shown by these workers that when $\gamma = 1.0$ the negative is the true inverse of the original; when greater than 1.0, the contrasts of the original are increased; while if less than 1.0, they are diminished. In testing by diffused daylight it is not possible to obtain the values of $E_1 E_2$ expressed in c.m.s. (candle-meter-seconds); nor for practical results is it essential. If one takes instead the ratio of the light-apertures in the revolving sector-plate, results of sufficient accuracy may be readily secured.

In the sector-disk made by the writer the apertures were cut in brass with much care, and the edges beveled. Yet, notwithstanding all efforts to the contrary, the error on the smaller apertures was considerable. This error may be noted by comparison with the theoretical ratio, thus:

Theoretical ratio = 1, 2, 4, 8, 16, 32, 64, 128, 256
 True ratio = 1.04, 2.03, 4.06, 7.94, 15.83, 31.84, 63.8, 127.6, 256.0¹

When it is borne in mind that in the everyday practical sensitometry of photographic plates use is made of those obtainable commercially, and not of an article specially coated on an accurate surface, it will readily be appreciated that the use of the theoretical aperture-ratios is well within the limits of "plate error;" to make use (except for special work) of the true ratio is an unnecessary refinement.

The value of γ may also be obtained graphically by drawing a line parallel to the straight portion of the characteristic curve, start-

¹ My best thanks are due to Professor Raymond Burnham, of the Armour Institute, Chicago, for the measurement of the disk apertures.

ing from the point 1.0 in the log E scale; for, as expressed by Hurter and Drifford, $\gamma = \tan \theta$, where θ is the angle of inclination of the curve from the horizontal base-line. The value is read directly from the scale of density-ordinates. In practice the writer finds it convenient to shift this 1.0 point two divisions to the left along the abscissa scale, and thus economize space.

The constant t_{γ_1} (the time necessary for any plate to reach a development factor of 1.0) advanced by Mees and Sheppard, which is of great value in the indication of the development speed of various plates, may be determined by the method of Drifford for determining

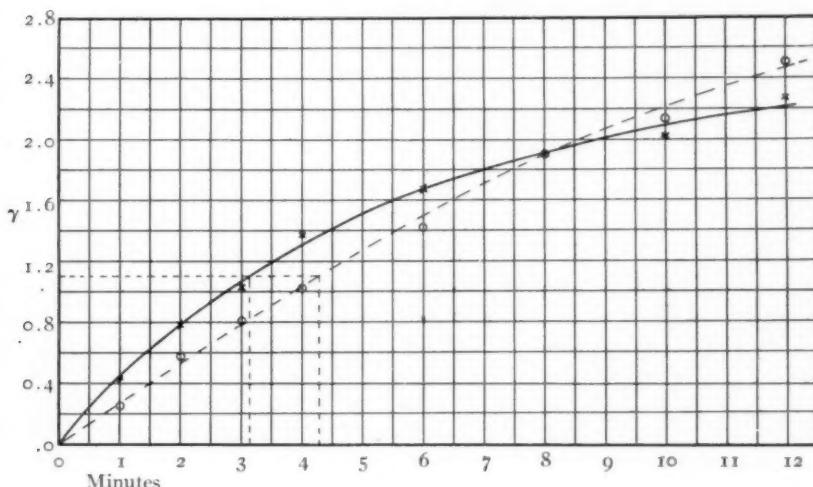


FIG. 11

the "control factor."¹ The development factors (γ), extracted as already described, are now plotted with the time of development as abscissae, and the two development factors as ordinates, which together with the zero point determine the curve. Take, in illustration, the Seed "27" and Cramer "instantaneous isochromatic" plates (Fig. 11), which were exposed behind the sector-disk and developed at a temperature of 17° C. for from 1 to 12 minutes, respectively. From the replotted curves in Fig. 11 the development time necessary to reach $\gamma_{1.1}$ may be read off directly as indicated—viz., 3^m 10^s and 4^m 15^s, respectively.

¹ *Photographic Journal*, 43, 17, January 1903.

RELATIVE SPEED

The method now advanced by the writer consists in selecting some one plate whose quality and general behavior present a reliable uniformity against which all other plates may be compared. In the Seed "27" Gilt Edge we have a plate which may fairly be considered as filling the requirements, because, in spite of the fact that occasionally it has suffered a slight drop in speed, it is characterized by a remarkable uniformity.

Briefly, the speed of a plate is required to be known. It is cut in such a manner that it, together with a "27," may lie in the holder and be exposed at the same time behind the revolving sector-disk to the same light-intensity. After exposure, each plate is cut into two strips, and all are developed at the one time and at constant temperature, being removed from the developer in pairs after the lapse of 4 and 8 minutes, respectively, and then fixed, washed, dried, and measured.

From these measurements is extracted γ , and the time necessary to reach, say, $\gamma = 1.0$, is read off directly, and used as a time-factor for the development of another pair of exposures upon two more of the same plates developed at a similar temperature.

The measurement of this second pair of plates will in turn give curves which lie parallel to one another, and from which the relative speed may be obtained.

One measures, therefore, the distance apart of the curves (horizontally), and, remembering that the exposure increase for each step rises in powers of two, the difference in speed between the two plates for a given intensity of light of similar spectral composition will be two, raised to a power the value of which will be determined by the distance measured; e. g., the mean distance apart of the two curves in Fig. 9 is 3.2, then $2^{3.2}$ is the difference in speed; or, the exposure time would have to be increased 9.19 times in order to obtain similar density.

In this method of relative speed determination there is the extra work entailed by the measurement of the "27" plate with every determination, but such work really amounts to very little in actual time, and has the added advantage in the use of daylight in place of some artificial "standard" of more or less doubtful value.

Experimentally the writer has not been able to so accurately expose and develop a third pair of plates as to have the plotted results actually superpose, the difference from a mean curve being ± 0.02 of a density unit in the most favorable instances, and running up as high as ± 0.05 in exceptional instances. Further discussion upon this and kindred points is reserved for a following paper.

COLOR-SENSITIVENESS (χ)

When Hurter and Driffield advanced their epoch-making methods for the sensitometry of photographic plates, the use of a candle in this connection was allowable, because at that time the orthochromatic plate was but little used and less generally understood. At the present writing there is scarcely a manufacturer of photographic plates throughout the world who does not prepare one or more brands of color-corrected plates, and it is merely a question of a very brief time until the use of the orthochromatic plate will be imperative for everything save the photography of black and white.

When we consider the color-sensitive plates of the present day as a whole, there are four points which strike even the casual observer as characteristic: (1) the *strong* sensitiveness to the blue-violet; (2) the secondary sensitiveness to the yellow-green; (3) the *low* sensitiveness to the blue-green; and (4) the lack of sensitiveness to the red. It is evident that these values should be definitely known, and that, whatever method is adopted for their estimation, it should be comprehensive enough to thoroughly differentiate them.

Mees and Sheppard have proposed the constant χ as representing the ratio of the inertia of the blue-sensitiveness to the inertia of the yellow-sensitiveness. Their method of determining this value (which is an improvement upon the system of Eder) consists in exposing a plate to their screened acetylene light behind the sector-disk, which plate is still further screened by the interposition of a color-filter transmitting only the red light to $\lambda 5900$ (A-D).¹ Another plate is exposed in the same manner, but with the interposition of a green

¹ The spectral transmission value of this color-filter should be very carefully determined, as it is composed of rose bengal and tartrazine. This latter dye even in concentration transmits the ultra-violet at $\lambda 3700$. The rose bengal of course transmits the violet very fully.

filter transmitting light from $\lambda 5900$ to $\lambda 5000$ ($D-b\frac{1}{2}F$), while a third plate is exposed through a blue filter transmitting light from $\lambda 5000$ on ($b\frac{1}{2}F+$). The densities of these plates are then measured, and the ratio of the inertias is obtained.

In the opinion of the writer, the division of the spectrum into three parts furnishes altogether insufficient information for either the scientist, plate-maker, trichromatic worker, or student of orthochromatism.

A plate exposed through the red color-filter may give a very high value, and thus indicate a red-sensitiveness which does not exist, the action being due entirely to the orange at, say, $\lambda 6000$, to determine which reference *must* be made to the spectrum. A somewhat different criticism applies to the results obtained by exposure through the green filter, whose transmission ends in the region of photographic low-sensitiveness in the blue-green. The elimination of this insensitive gap (or results tending to such elimination) is of considerable importance in practical plate-making, and therefore the relative values of plates for this region should be definitely recorded; the division of the spectrum at this point by the green and blue filters makes such determination impossible.

The method, however, has a certain broad value for the estimation of sensitiveness when required for use with wide-banded color-filters, such as are generally used in trichromatic work; but it is unquestionably true that it cannot compare in quantitative estimation with a series of daylight spectrum negatives where the action of the plate for every wave-length of light is definitely apparent. As any system of sensitometry to be popular must be rendered as simple as is consistent with definiteness, then what could be easier than to quote the density-readings at, say, six points¹ of the spectrum measured, if any further numerical evaluation be required?

DEVELOPMENT OF SPECTRA

In the development of the spectrum plates obtained by exposure in the spectrograph as described, special care must be taken to hold as constants (a) the constitution of the developer; (b) the tempera-

¹ The six points referred to may be at $\lambda\lambda 3800, 4100, 5100, 5500, 5900, 6100$, for all of the ordinary orthochromatic plates. In cases of special red-sensitiveness then the density-value of a seventh point may be added.

ture of the developer; (*c*) the time of development (as determined by the γt curve and corresponding sector-strip). Due attention to these points will result in negatives directly comparable with one another.

MEASUREMENT AND INTERPRETATION OF SPECTRA

In a series of spectrum exposures upon two different plates, that one of each is selected for measurement whose region of maximum opacity corresponds approximately to a density of 2.5. This is very readily selected by comparison with a standard density plate upon which the measured densities have been plainly marked.¹ Now, it makes absolutely no difference whether this spectral maximum lies in the yellow or in the violet. The only thing to take for is a maximum of 2.5.²

In the practice of the writer this is still more readily determined by setting the analyzer circle of the spectro-photometer at 3° , and moving the spectrum plate in front of the collimator slit until we arrive at that one whose maximum opacity approximately equalizes the field in the viewing telescope; then that spectrum is marked for measurement. With a similar procedure on other plates we obtain spectra which may be compared directly with one another, because, generally speaking, they represent as their maximum an opacity of action of 256 light-ratio units, under identical conditions of development.

Using a narrow slit in the spectrophotometer, the spectrum selected may now be measured, and its curve plotted in the usual manner, with the densities expressed as ordinates and the wavelengths as abscissae; or, if preferred, the ordinates may read light-unit ratios, the values being obtained by interpolation upon the curve already obtained from the corresponding sector-disk negative previously exposed and developed at a similar temperature, and taking the aperture ratios as units. This method was advanced by the writer in a former paper,³ and serves the very useful purpose of indi-

¹ Such a plate may be obtained from a Scheiner or a Hurter and Driffield sector-disk.

² Because 2.5 is conveniently the highest allowable density for reliable direct measurements.

³ "Preliminary Note on Orthochromatic Plates," *Astrophysical Journal*, **22**, 153, 1905. It should be mentioned, however, that the values given in this former paper were from visual *estimates*, in place of the present *measures*, although the following paper (*ibid.*, **22**, 350, 1905) confirms by experiment the values first derived.

cating at a glance the ratio of opacity to exposure for differing wave-lengths.

In such a spectrum record we obtain a quantitative estimate of the plate under test. Aside from the spectrum selected for measurement, we see at a glance the true region of maximum sensitiveness as evidenced in the shorter exposures. The growth of density in the least refrangible region with increase of exposure is readily marked, and its relation to the blue-sensitiveness may be easily approximated when the exposure time is known. If, for example, the spectrum selected for measurement as having normal exposure be the resultant of an exposure of a minutes, then the value x of the light-units acting at any point on some other exposure b may be expressed as $\frac{a}{b}c = x$, where c is the value of the light-units corresponding to an exposure a .

Furthermore, we do not have to depend upon the impress of a glass scale (for example) in order to record spectral position, into which there enters an element of uncertainty consequent upon the accidental displacement of either that or the dispersion-piece. On looking at a print from such a record, the observer has absolutely no means of knowing whether the scale is in true position or not, or to what extent the negative may be overexposed. On the other hand, the daylight record leaves no element of uncertainty, because the Fraunhofer lines indicate at a glance the exact wave-lengths, and also serve to show over- or under-exposure.

In all of the spectra exposed above normal there is present an amount of "fog" which arises from the "spreading" of the light at the region of maximum sensitiveness, and interior reflection in the spectrograph; furthermore, the overlapping ultra-violet of the second-order spectrum is apt to lead to false conclusions in the estimation of color-sensitiveness. For that reason the remaining two exposures are made after introducing the wedge between the collimator tube and the front board of the camera, the increase in the angle of incidence thus causing a corresponding displacement of the spectrum on the plate. An ammonium picrate color-filter is then introduced in front of the slit to completely absorb the overlapping violet. These latter two exposures are necessary to the correct appreciation of the actual extent of sensitiveness in the red. The appearance presented

by such a negative plate as has been described is shown in *j*, Plate VIII.

It should be definitely understood that this suggested method of daylight sensitometry is advanced as a practical everyday means of arriving at reliably comparable results suited to the requirements, not only of the general worker in photography, but also of those who are making use of the photographic plate in obtaining records of scientific value. No one is more conscious than the author that it contains some points which may in time be improved upon, but it at least serves the useful purpose of definitely pointing out in connected form the greater number of pitfalls and inaccuracies which beset the path of sensitometry, and further indicates a means of obtaining exceedingly good results with the minimum of time and equipment. It will be obvious that the method is primarily suited to those who are *users* of plates, rather than to those whose work tends principally toward the *manufacture* of the material. For this latter class, however, there is no reason why the method may not be extended to embrace the requirements suited to their needs.

SUMMARY

We may summarize the foregoing and tabulate the entire process as follows:

1. The advancement of the replica-grating as a standard dispersion-piece, together with a simple form of spectrograph suited to its use.
2. A suggested method of daylight sensitometry (making use, as far as possible, of the laws discovered by Hurter and Driffield), of which the following is a résumé:
 - a) Exposure of one $2 \times 4\frac{1}{2}$ plate scored down the back, but not broken through, together with one $2 \times 4\frac{1}{2}$ Seed "27" plate, for, say, two minutes, in the sector-disk machine.
 - b) The scored plate is broken through into two secondary slips, and all four plates are now developed (preferably together) with a constant developer, for a constant length of time, and at a constant temperature, with the exception of one of the secondary slips which remains in the developer for exactly double that of the others.

- c) Measurement of the density strips and extraction of γ , t_{γ_n} and latitude.
- d) Exposure of a second pair of $2 \times 4\frac{1}{2}$ plates, and development for the time necessary to obtain equal amounts of development action as found from d, retaining composition of developer and temperature as constants. Measurement of same and extraction of speed-ratio.
- e) Exposure of one $3\frac{1}{2} \times 4\frac{1}{2}$ plate to a series of eight exposures in the spectrograph varying from two seconds to eight minutes, and two further exposures on the same plate with the collimator wedge in position and through the ammonium picrate screen.
- f) Measurement of selected spectrum for quantitative color estimation.

YERKES OBSERVATORY,
January 24, 1907

REVIEWS

Introduction to Astronomy. By FOREST R. MOULTON. New York: The Macmillan Co., 1906. Pp. 557, with 201 figures and 4 star maps. \$1.25.

The appearance of an introductory treatise on astronomy by Professor Moulton is of interest to all readers of science, and of special interest to teachers of astronomy. Professor Moulton's point of view is his own, in many ways unlike that of the textbooks in general use. Although the order and emphasis of presentation may be sometimes criticized, there can be no question that the book is throughout suggestive and stimulating.

The introductory chapter is a new feature. It offers a preliminary outline of the whole subject, the author holding that a brief survey of the science is desirable, in order that main lines may not be lost sight of in details. It contains a good statement of the method of scientific inquiry, and an excellent presentation of the steps of evolution in astronomy.

The chapter on co-ordinates gives good suggestions for approximate naked-eye use of co-ordinates; and, indeed, throughout the treatise the examples combine practical relations with common-sense theory to an unusual degree. Professor Moulton does not eschew philosophy and psychology in the problems he considers. In his discussion of time he sets forth its psychological aspect quite fully.

The author gives an early chapter to constellations, and he combines with the description of each constellation the leading facts regarding proper motion, parallax, variability or spectroscopic binaries, which the group presents. For an understanding of these terms, so far in advance of the stage reached, the introductory outline provides a sufficient basis.

Another novel feature is the treatment of earth and planets in one group, rather than the ordinary separate treatment of the earth's motions followed by that of the planets. Although logical, it may be questioned whether this method would be equally clear and satisfactory for the average student. Further, in the case of the earth's motions, a larger familiarity with the actual phenomena of the sky is desirable, before the chapter is reached in which they are treated. The degree of ignorance which the average young person carries in regard to the rising and setting of the

celestial bodies and other fundamental phenomena is amazing. It has been my custom to ask a series of questions bearing upon these immediate facts of observation, before taking up the study with a class of beginners. I find a large measure, not only of ignorance, but of confused misapprehension of what is to be seen in the sky.

The historical view of the planetary theory is clearly and concisely given, with unnecessary details wisely omitted. The application of the heliocentric theory to the observed motions might well be more fully developed. Few students could pass from theory to observation without further guidance than the text offers. These problems of planetary position are more immediately connected with the early development of the science than any others, and they are within the firmer grasp of the average beginner than the dynamic questions to which Professor Moulton devotes more attention. He has before now given expression to his preference for dynamic relations in instruction as against those of position, but a longer training is necessary to clear thinking in these lines than the beginner usually possesses.

Professor Moulton describes the work of Kepler and Newton in an admirable manner—clear, concise, and interesting. The presentation of perturbations, always difficult to lay before a class with clearness and brevity, is extremely well put, with due precautions regarding ultimate conclusions. In the chapters on the solar system there is much to commend. Here, as elsewhere, the author gives very simple and illuminating illustrations, as, for instance, of the parallax of the sun, the uncertainty in the determination of comets' orbits, the theory of light production and absorption. Perhaps undue time is afforded to the zodiacal light and the gegenschein, to the curtailment, for instance, of methods of finding the solar parallax. The chapter on comets and meteors closes with a good statement of the investigations now needed to establish a better knowledge of these bodies and their relations.

The placing of the chapter on the constitution of the sun is another unusual feature. It is postponed to the close of the section devoted to the solar system, standing between it and the consideration of the stellar system. This is well chosen, in view of the great prominence now given to the sun as a star. The brief description of the spectroheliograph, with a clear and simple figure, contained in this chapter, will be welcomed by teachers of astrophysics.

Chapter xv, devoted to theories of evolution, is full of matter. The value of a theory in itself as a stimulus to investigation is dwelt upon. Darwin's tidal theory is fairly criticized. The planetesimal theory of

Chamberlin and Moulton—called in the text the spiral nebula theory, to distinguish it from the Laplacian theory—is given in considerable detail. If the theory holds its ground in the future, the space given to it in the treatise will not prove excessive. But if it fails to make a good showing, later editions will curtail its limits. It may be questioned whether in a textbook for beginners so large a share of attention should be given to a theory which has not yet undergone general discussion by the world of astronomers. But its deep interest and its rich suggestiveness lead one to overlook the propriety of its setting.

The illustrations are generally good. Some of the figures might, to advantage, be somewhat larger. The fine photographs of stars and nebulae obtained in recent years at our leading observatories are well reproduced. The star maps, bound with the text, will prove convenient for class use.

MARY W. WHITNEY

Sternverzeichnis enthaltend alle Sterne bis zur 6.5^{ten} Grösse für das Jahr 1900. Bearbeitet auf Grund der genauen Kataloge und zusammengestellt von J. und R. AMBRONN. Mit einen erläuternden Vorwort versehen und herausgegeben von DR. L. AMBRONN. Berlin: Julius Springer, 1907. Pp. 183. M. 10; interleaved for notes, M. 12.

This compact catalogue, containing in 158 pages the positions of 7796 stars of magnitude 6.5 and brighter, cannot fail to be of the greatest service to astronomers generally. The arrangement of the work is particularly to be commended, and makes its use rapid and very satisfactory. In addition to a current number, there is given the name of constellation, with Bayer's letter and Flamsteed's number (if any); the magnitude (for northern stars from the Potsdam photometric Durchmusterung; for the southern stars from the "Uranometria" of Pritchard and the Harvard photometries); the right ascension to tenths of seconds of time, and the declination to seconds of arc, with annual variations; the reference to the catalogue from which the position is taken, and the *B. D.* number; and finally a column of remarks. Foot-notes refer to stars interesting by reason of duplicity or variability, and give the individual names of the brightest stars. The letter *e*, conspicuously placed in the *A. R.* column, indicates that the proper motion is given in the list of *Eigenbewegungen* occupying 18 pages at the end of the catalogue.

The precision of the places is entirely adequate for all spectroscopic and photometric purposes, and the reference to the original catalogue makes a greater precision immediately available where necessary.

Professor Ambron is to be congratulated in having in the persons of his wife and son able coadjutors, who performed the great part of the reductions and prepared the manuscript for publication.

The book will be needed in every observatory and by all field astronomers and there will be few teachers of astronomy who could not use it at times to great advantage.

E. B. F.